Hacia un Ciclo de Combustible Nuclear Sustentable

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REMECIN
Red Mexicana de Educación, Capacitación e Investigación Nuclear

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SOCIEDAD NUCLEAR MEXICANA

Academia de Ingeniería México

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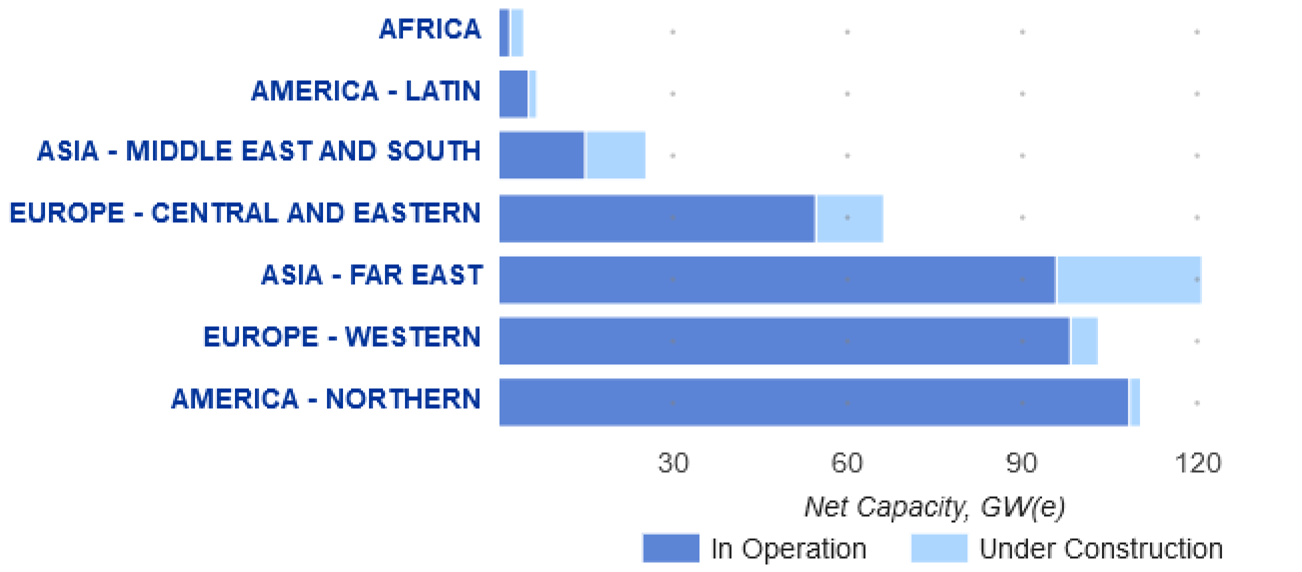
IAEA | PRIS Power Reactor Information System

CURRENT STATUS

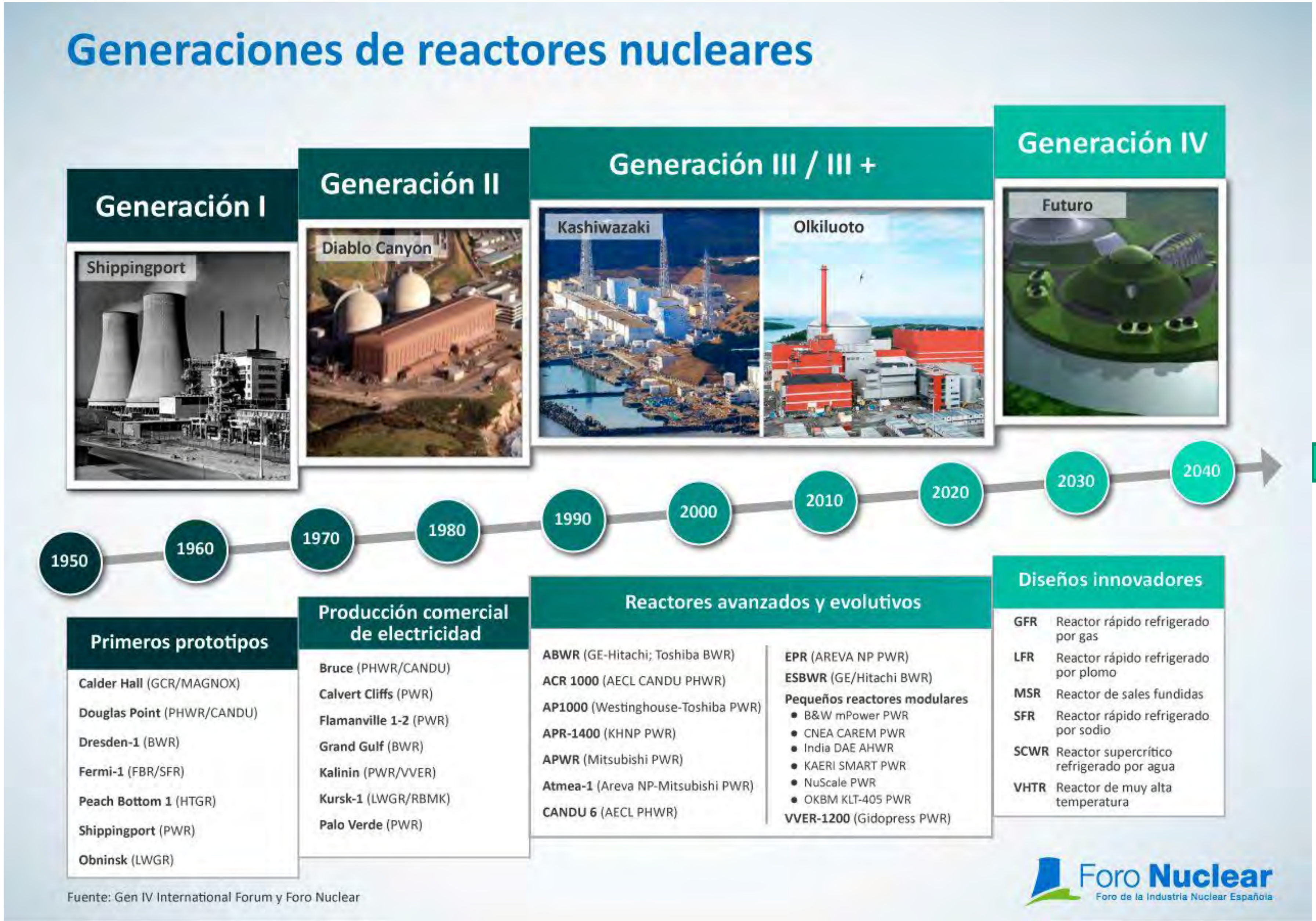
423	NUCLEAR POWER REACTORS IN OPERATION
378 754	MW_e TOTAL NET INSTALLED CAPACITY
17	NUCLEAR POWER REACTORS IN SUSPENDED OPERATION
15 448	MW_e TOTAL NET INSTALLED CAPACITY
56	NUCLEAR POWER REACTORS UNDER CONSTRUCTION
58 418	MW_e TOTAL NET INSTALLED CAPACITY
19 440	REACTOR-YEARS OF OPERATION

REGIONAL DISTRIBUTION OF NUCLEAR POWER CAPACITY



World Nuclear Association: Requerimientos de uranio (2021) = 62,496 tU = 73,698 t U_3O_8

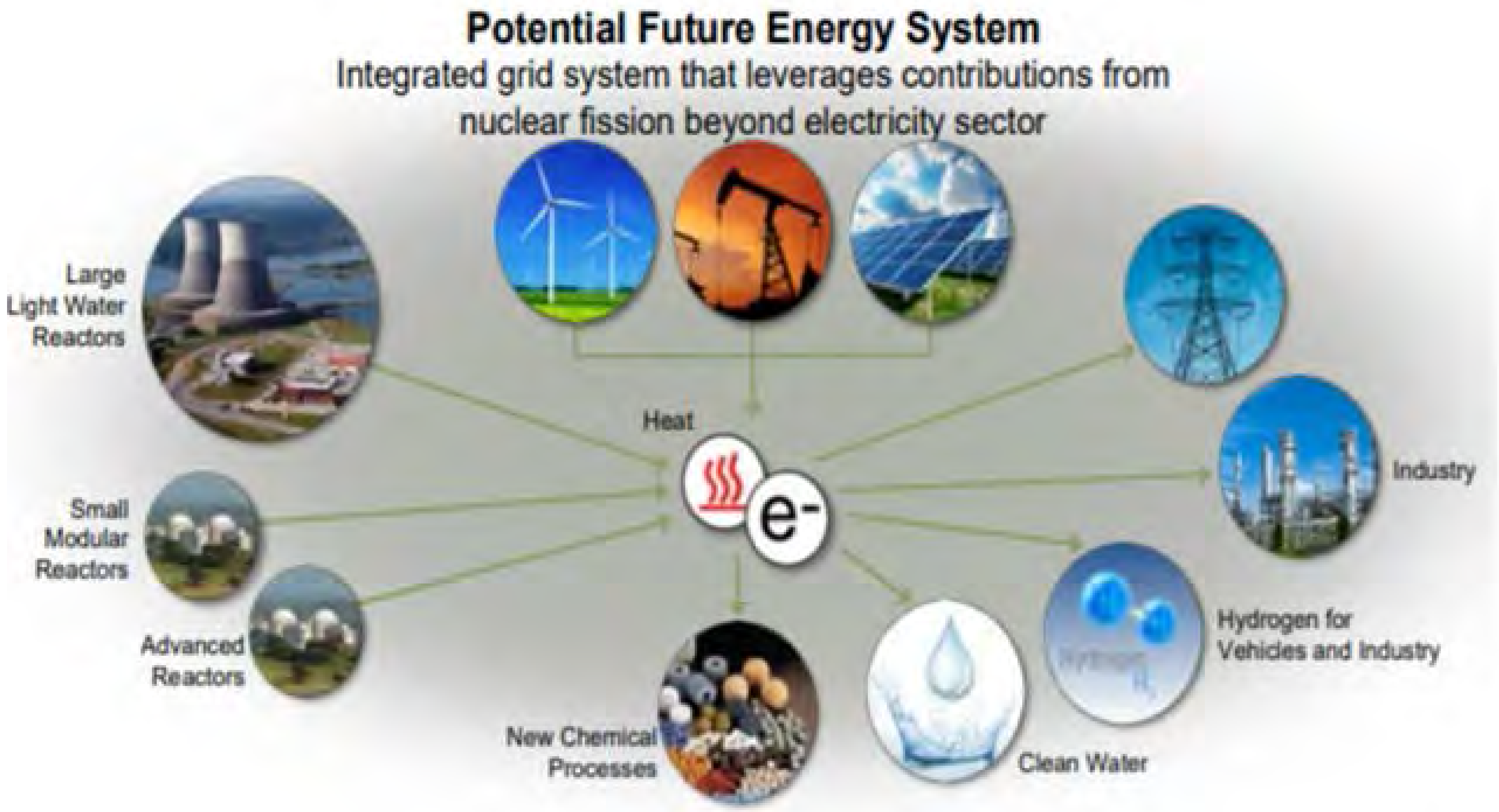
Aproximadamente 200 ton de U_3O_8 por reactor de 1000 MWe por año de operación

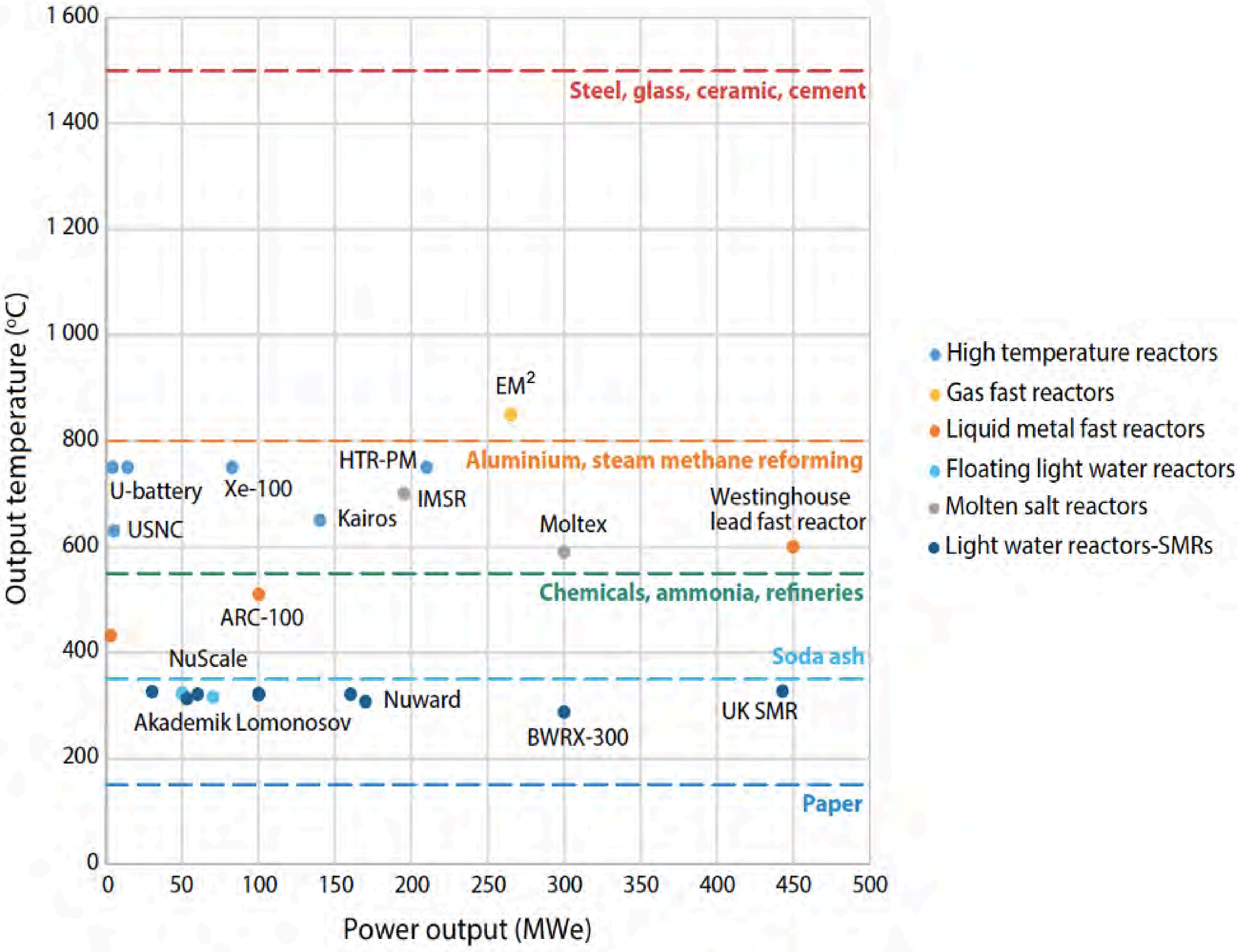


Producción de:

Potencia térmica

Potencia eléctrica en forma continua para todo tipo de aplicaciones energéticas


Potential Future Energy System
Integrated grid system that leverages contributions from nuclear fission beyond electricity sector
Large Light Water Reactors
Small Modular Reactors
Advanced Reactors
Heat
e-
Industry
Hydrogen for Vehicles and Industry
Clean Water
New Chemical Processes



NEA (2022). *Meeting Climate Change Targets: The Role of Nuclear Energy*. OECD .

www.oecd-nea.org/jcms/pl_69396/meeting-climate-change-targets-the-role-of-nuclear-energy

REUTERS®

Dow and X-energy to build U.S. Gulf Coast nuclear demonstration plant

https://www.reuters.com/business/energy/dow-x-energy-build-us-gulf-coast-nuclear-demonstration-plant-2023-03-01/

Xe-100

200 MW ...Thermal Output
80 MW ...Electric Output
750°C ...Helium Temperature
6 MPa ...Helium Pressure
565°C ...Steam Temperature
16.5 MPa ...Steam Pressure

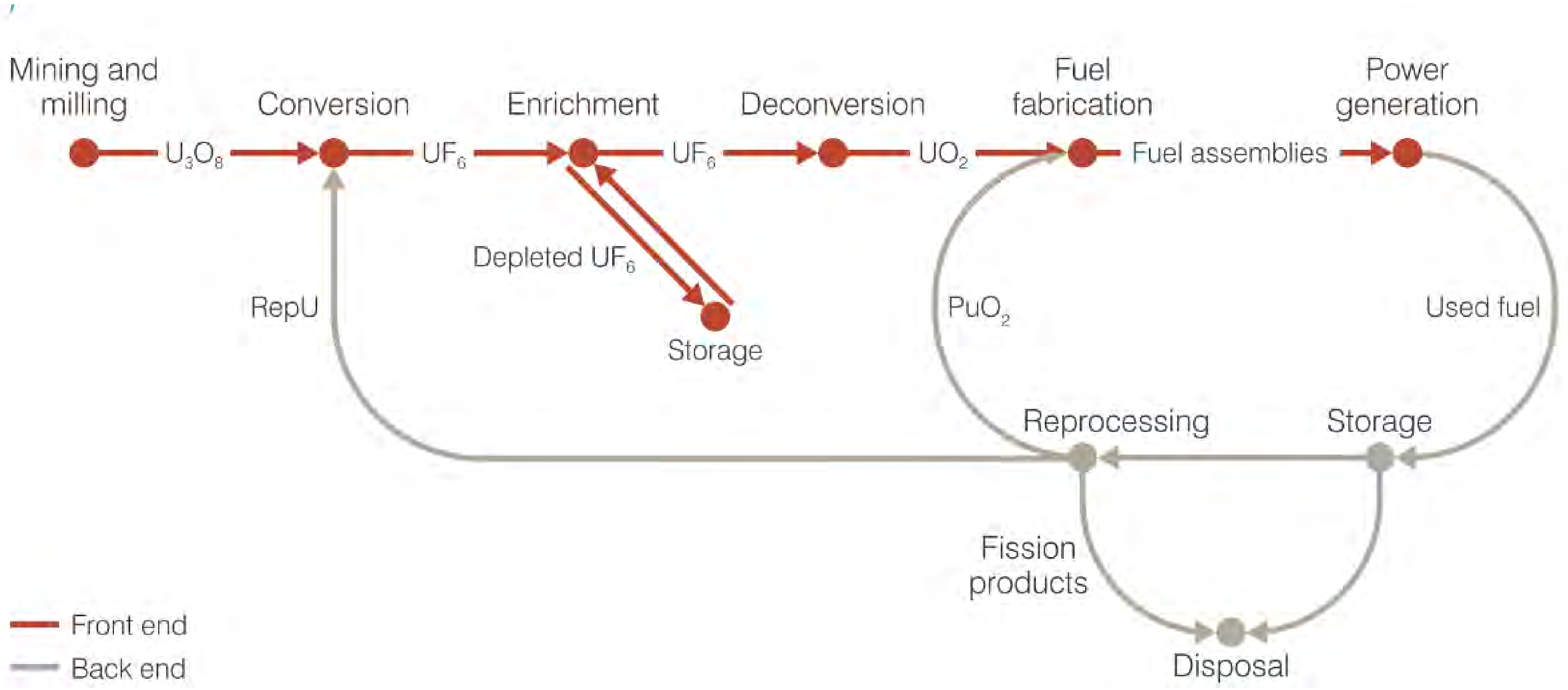
- 220,000 Graphite Pebbles with TRISO Particle fuel
- High temperature tolerant graphite core structure
- ASME compliant reactor vessel, core barrel & steam generator
- Designed for a 60-year operational life
- Flexible application – electricity and/or process heat
- Base load or load following
- Online refueling (95% plant availability)
- High burn-up fuel cycle (160 GWd/tHM)

https://nucleus.iaea.org/sites/smr/Shared%20Documents/SMR%20Booklet_22-9-22.pdf

Ciclo de Combustible Nuclear

U234	U235
2.455E+5 y	7.038E+8 y
0+	7/2-
α,n,sf,...	α,^{20}Ne,sf,...*
0.0055	0.7200

U238
4.468E+9 y
0+
α,β-β-,sf,...
99.2745



World Nuclear Association Image Library:
https://www.world-nuclear.org/gallery/the-world-nuclear-fuel-report-expanded-summary/the-nuclear-fuel-cycle.aspx

Parte frontal del ciclo de combustible – *Front end*

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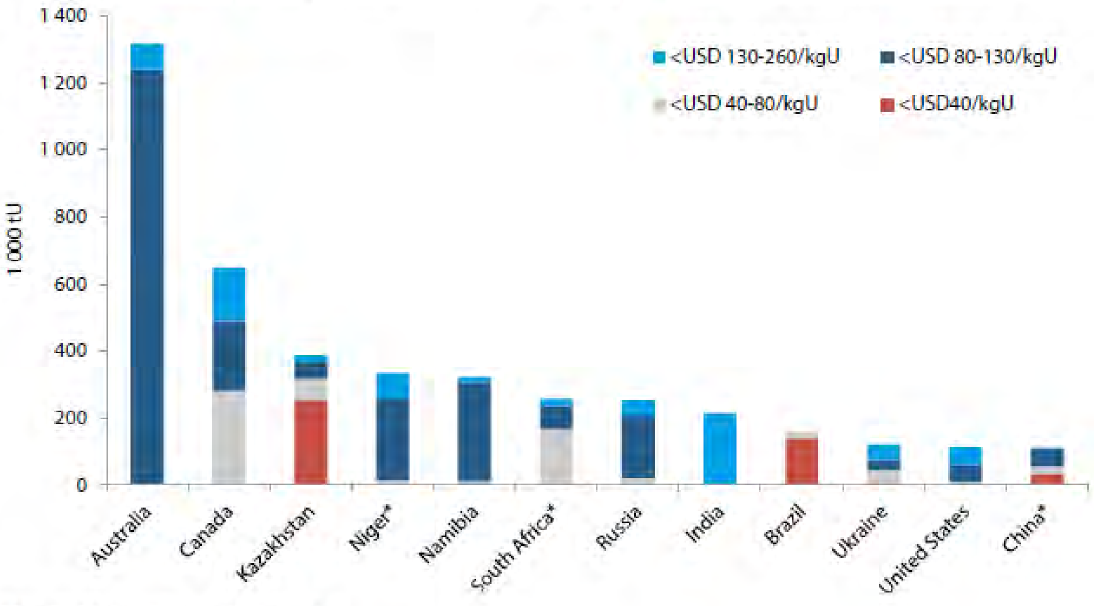
Uranio


Uranium ore (left) – pitchblende (right)
https://en.wikipedia.org/wiki/Uranium_ore

Figure 1.2. **Distribution of reasonably assured recoverable conventional uranium resources among select countries with a significant share of resources**



* Secretariat estimate or partial estimate.

Uranium 2022: Resources, Production and Demand (Red Book).
https://www.oecd-nea.org/upload/docs/application/pdf/2023-04/7634_uranium_-_resources_production_and_demand_2022.pdf

Open pit uranium mine.

Wikimedia Commons [Online]
https://upload.wikimedia.org/wikipedia/commons/5/51/Arandis_Mine_quer.jpg

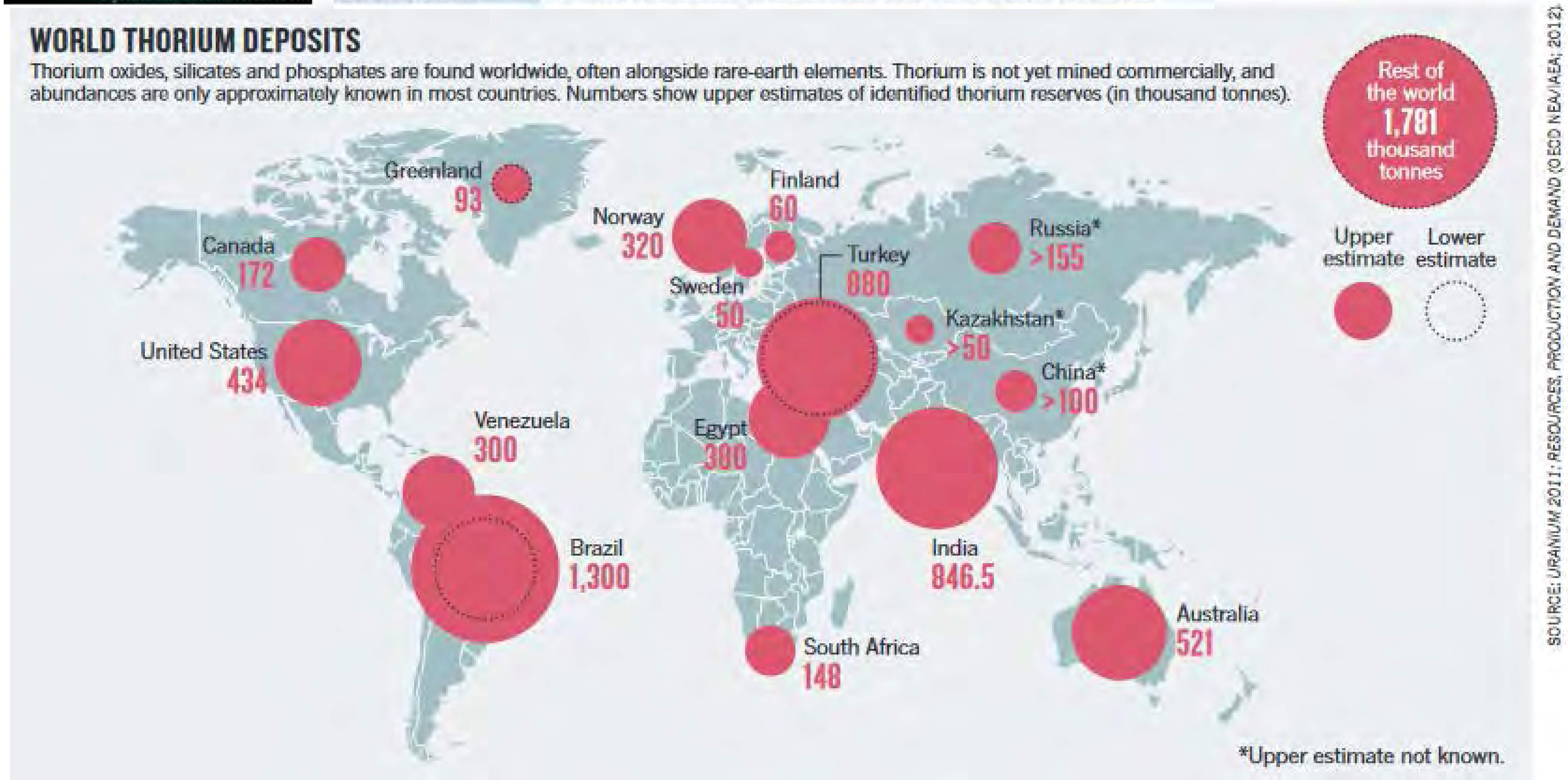
IAEA | INFCIS

Uranium Deposits (*)

https://infcis.iaea.org/UDEPO/Deposit/Map

Torio

Collection	John Betts - Fine Minerals
Description	Brown crude crystal of Thorite (var. Uranothorite) with visible termination on both ends. Mildly radioactive. Ex. A. Stevenson (1916-2007) collection #876.
Locality	Kemp Prospect, Cheddar, Ontario, Canada
Dimensions	15 x 14 x 13 mm.
Specimen Grade	B
Photograph	© www.johnbetts-fineminerals.com - All Rights Reserved.



Molienda

“Torta amarilla”: U_3O_8

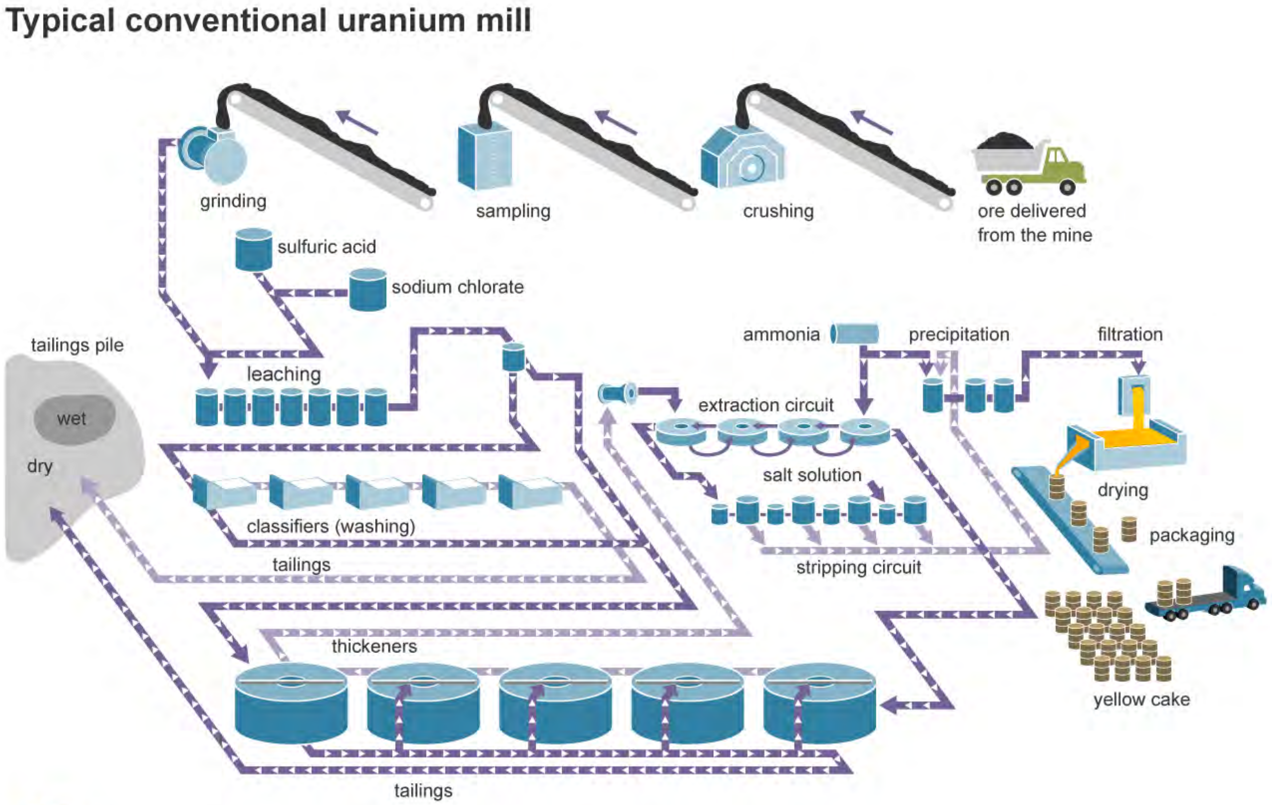
https://en.wikipedia.org/wiki/Yellowcake

Ux U3O8 Price - 2 Year History

The Ux Prices are copyrighted and owned by UxC, LLC. It should be noted that any reference, use or pictorial display of Ux prices **must be approved by UxC** and **must include** the line:

Source: UxC, LLC

and include a link back to UxC's home page at http://www.uxc.com/



Source: U.S. Energy Information Administration

https://www.eia.gov/energyexplained/nuclear/the-nuclear-fuel-cycle.php

Conversión

$U_3O_8 + 2H_2 ===> 3UO_2 + 2H_2O \quad \Delta H = -109$ kJ/mol

or $UO_3 + H_2 ===> UO_2 + H_2O \quad \Delta H = -109$ kJ/mol

This reduced oxide is then reacted in another kiln with gaseous hydrogen fluoride (HF) to form uranium tetrafluoride (UF_4), though in some places this is made with aqueous HF by a wet process:

$UO_2 + 4HF ===> UF_4 + 2H_2O \quad \Delta H = -176$ kJ/mol

The tetrafluoride is then fed into a fluidized bed reactor or flame tower with gaseous fluorine to produce uranium hexafluoride, UF_6. Hexafluoride ('hex') is condensed and stored.

$UF_4 + F_2 ===> UF_6$

https://world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/conversion-and-deconversion.aspx

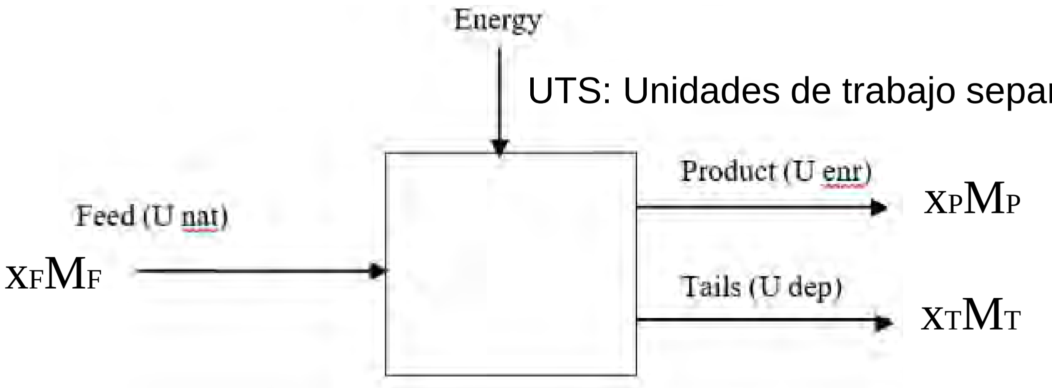
Estimated world primary conversion capacity 2020

Company	Country	Location	Nameplate capacity (tU)	Capacity utilization (%)	Capacity utilization (tU)
Orano*	France	Pierrelatte & Malvési	15,000	17%	2600
CNNC†	China	Lanzhou & Hengyang	15,000	53%	8000
Cameco	Canada	Port Hope	12,500	72%	9000
Rosatom	Russia	Seversk	12,500	96%	12,000
ConverDyn‡	USA	Metropolis	7000	0%	0
Total			**62,000**	**51%**	**31,600**

World Nuclear Association *Nuclear Fuel Report* (2021 edition)

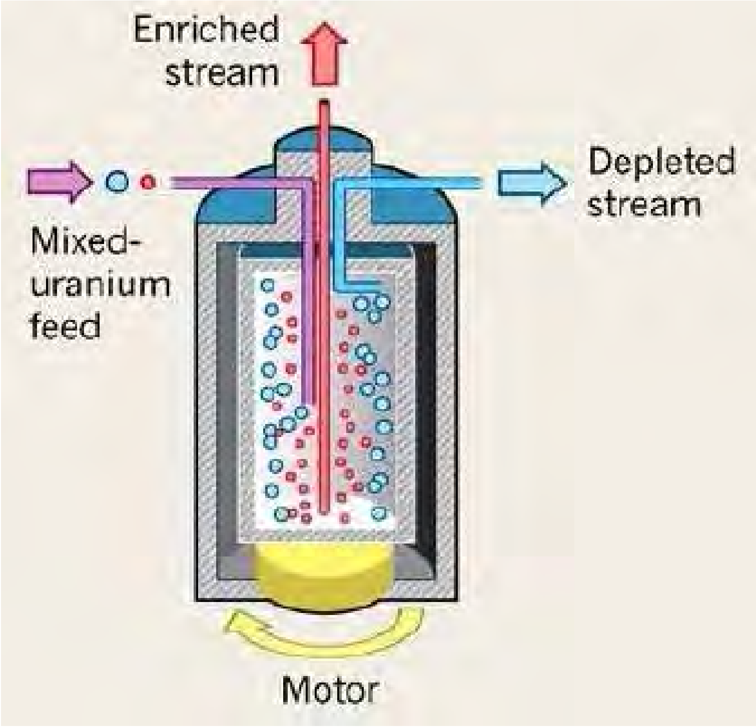
Enriquecimiento

UTS: Unidades de trabajo separativo

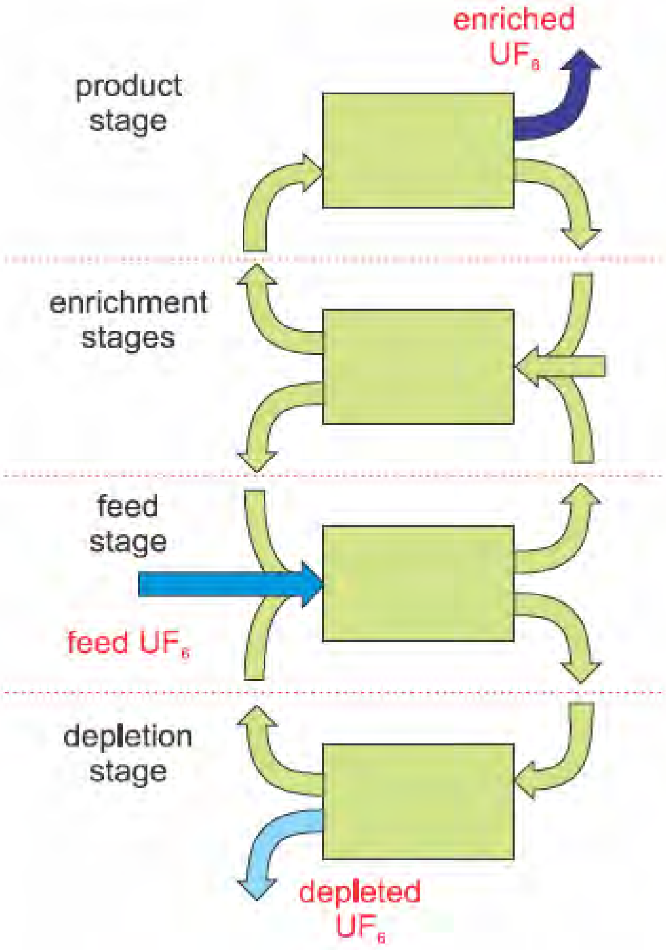


$$x_F M_F = x_P M_P + x_T M_T$$

Centrifugación gaseosa

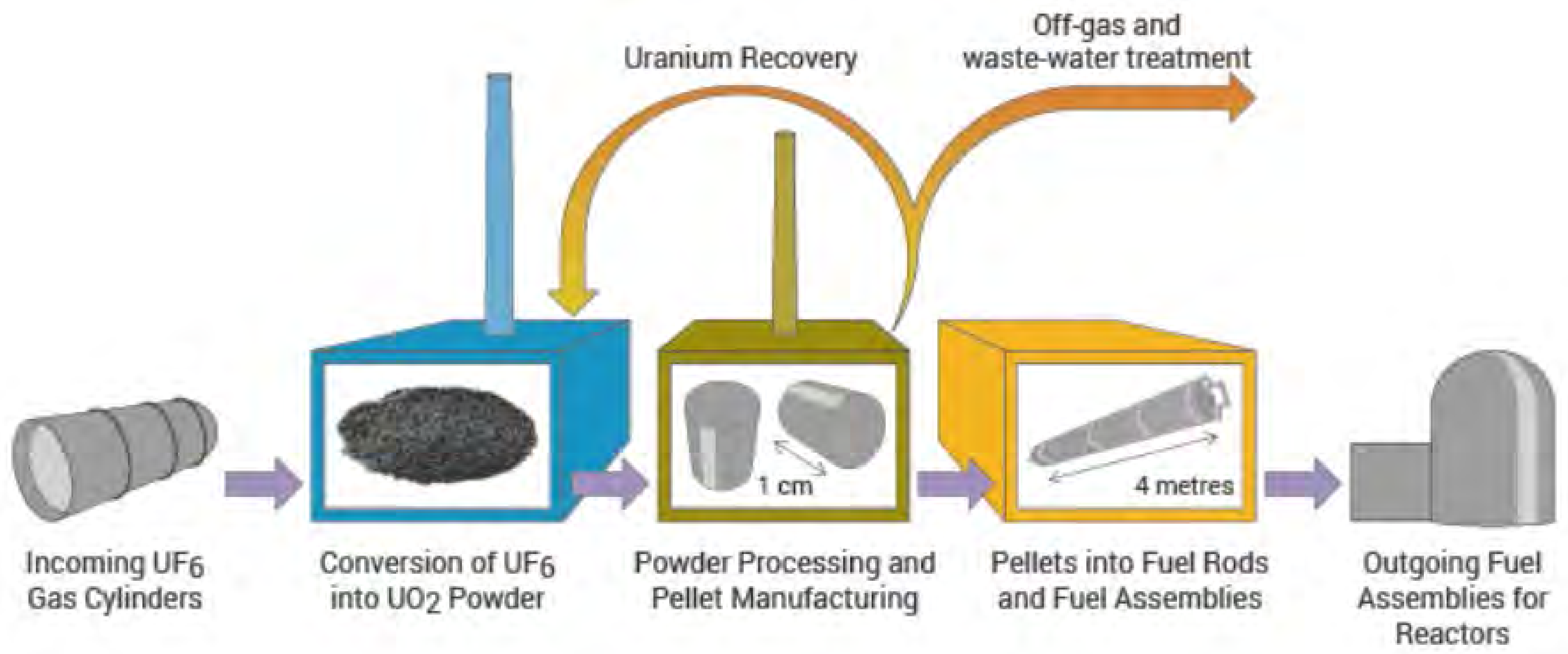


Basic Professional Training Course. Module XVII: Fuel cycle, spent fuel management and safety transport of radioactive materials. International Atomic Energy Agency, September 2015.



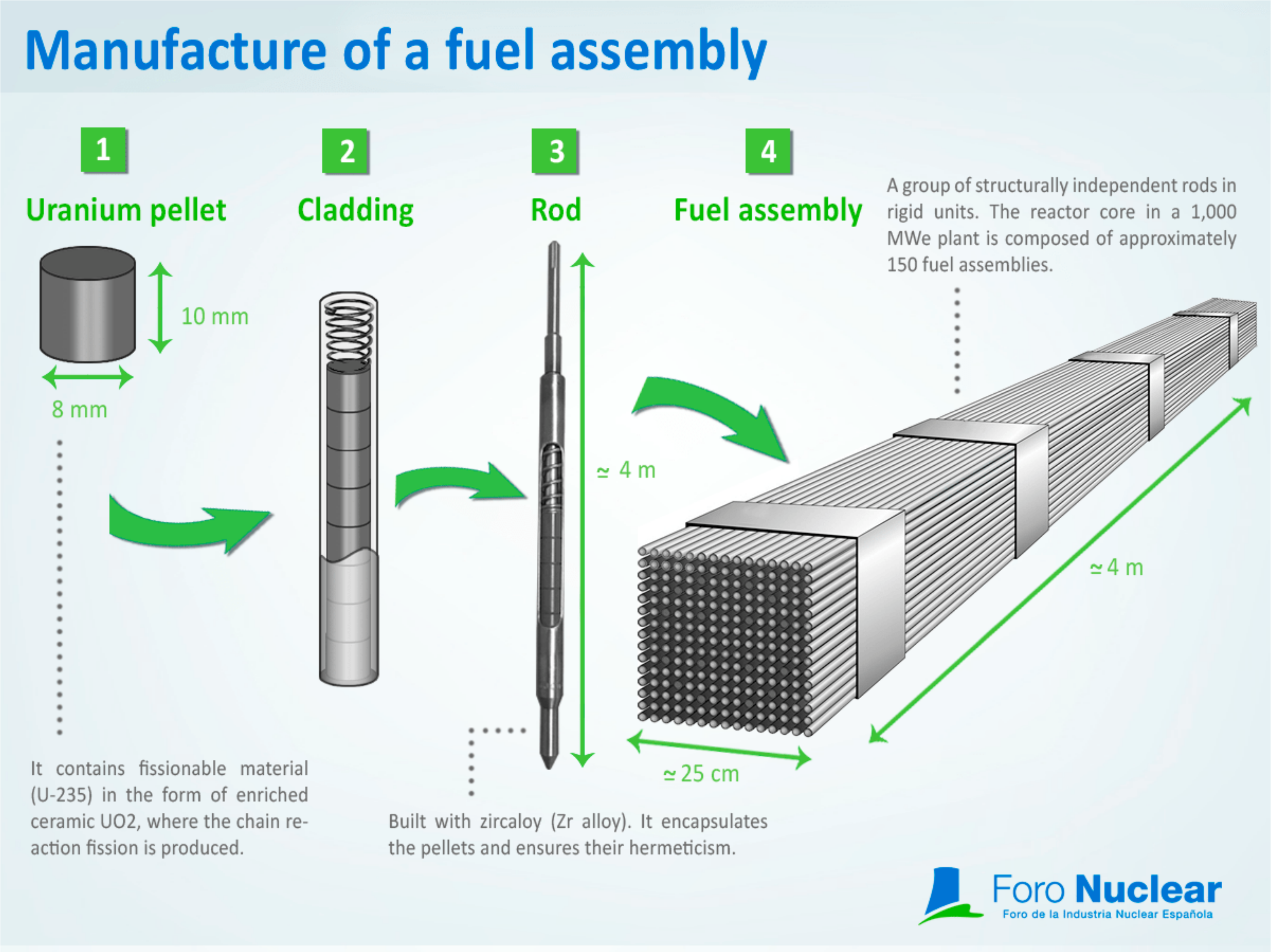
International Atomic Energy Agency, Nuclear Fuel Cycle Information System, 2009 Edition, IAEA-TECDOC-1613

Fabricación



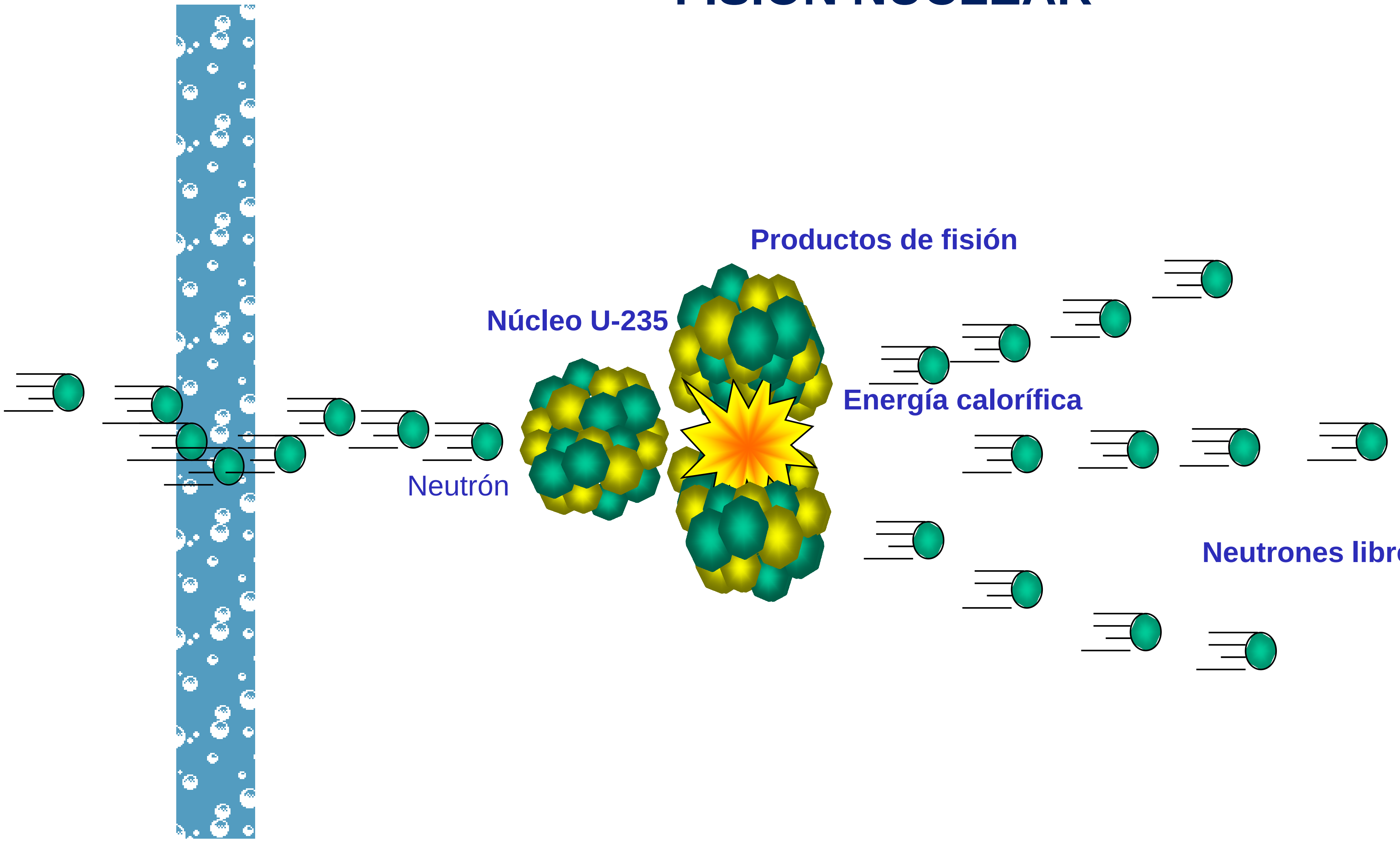
Fabricación de ensambles combustibles de reactores de agua ligera
WNA, https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/fuel-fabrication.aspx

Fabricación

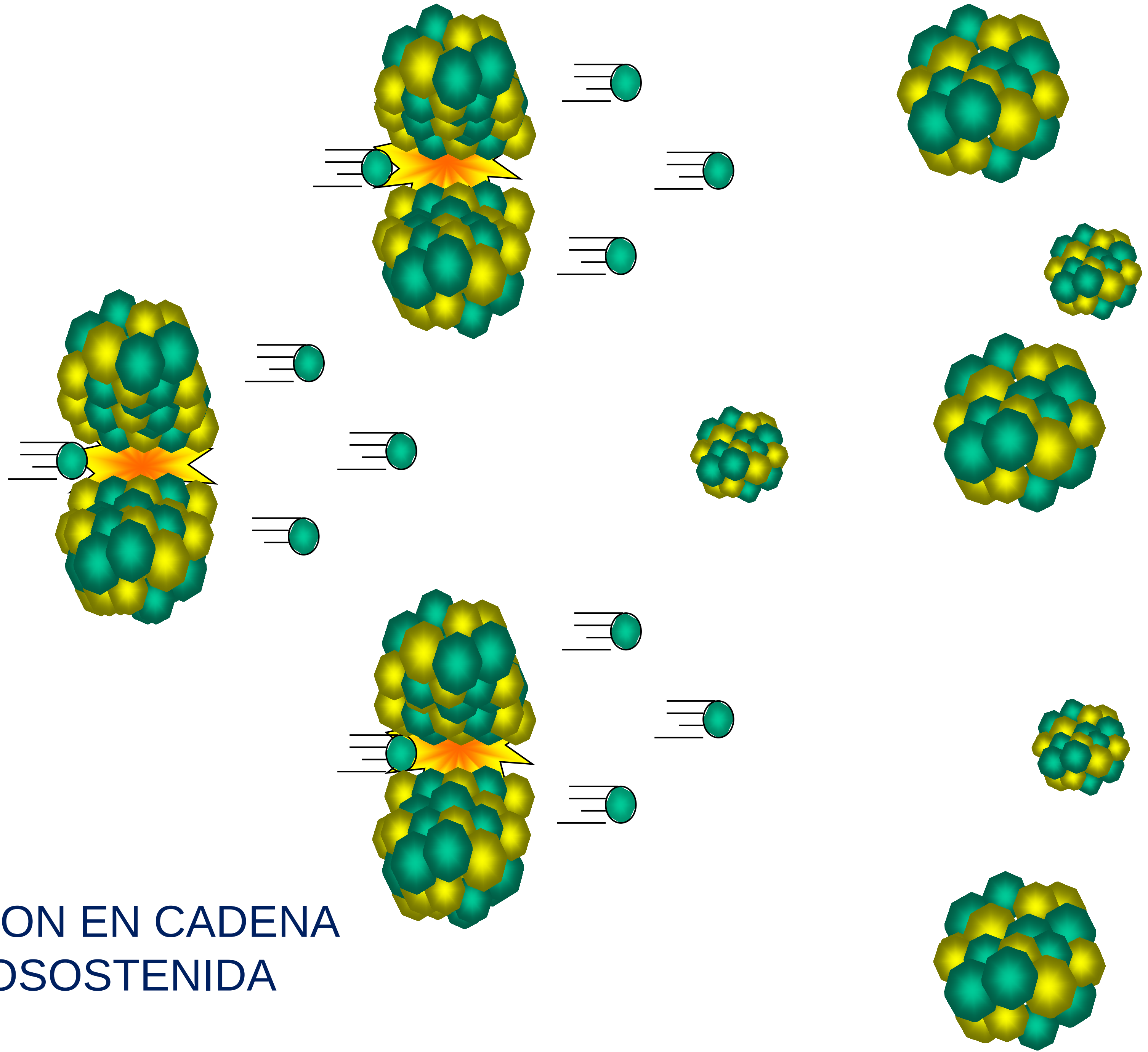


https://www.foronuclear.org/en/resources/infographics/manufacture-of-a-fuel-assembly

FISION NUCLEAR



AGUA PURA
MODERADOR DE LA VELOCIDAD DE LOS NEUTRONES



REACCION EN CADENA
AUTOSOSTENIDA

Reactores de neutrones rápidos: v = 14,000 km/s (Ec = 1 MeV)

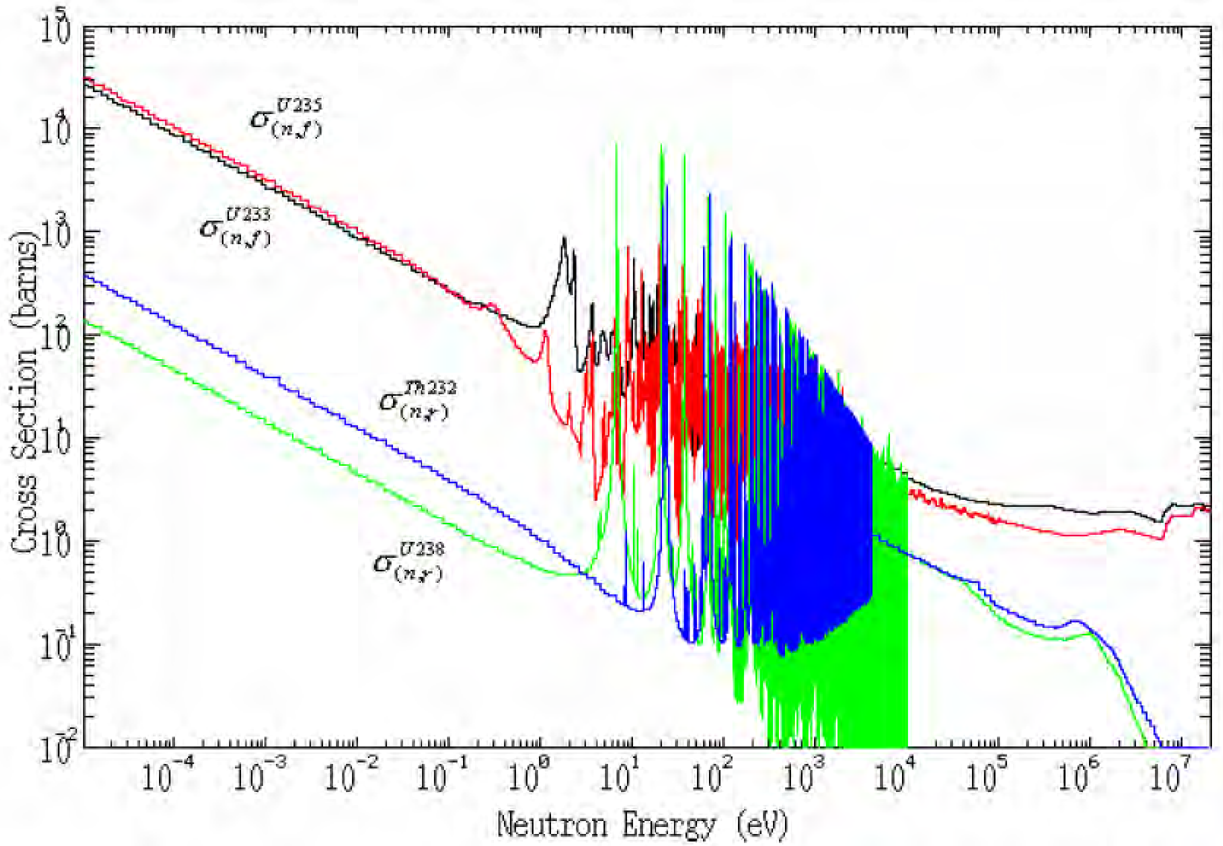
5 % < e < 20% U-235

→Cría y transmutación

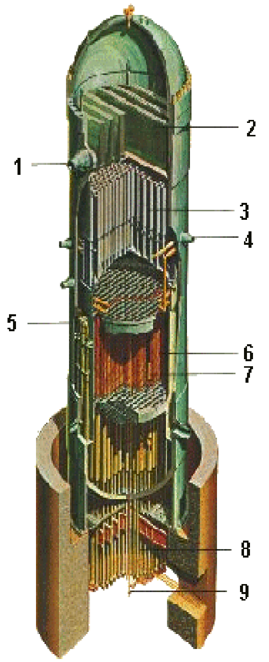
Reactores de neutrones térmicos:

v = 2.2 km/s (Ec = 0.025 eV)

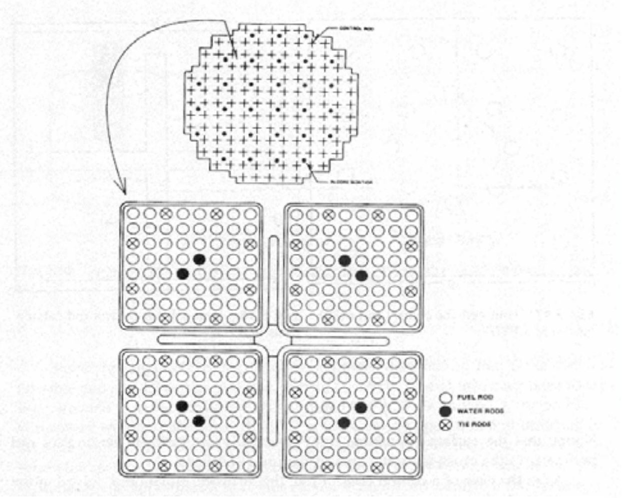
e < 5% U-235



Ciclo 1	Ciclo 2	Ciclo 3	.....	Ciclo N
Fecha, E, e, ..	Fecha, E, e, ..	Fecha, E, e, ..	Fecha, E, e, ..	Fecha, E, e, ..



CORTE DEL ENSAMBLE DE COMBUSTIBLE.



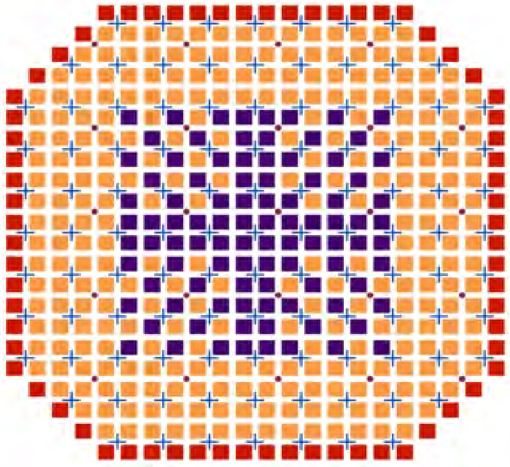
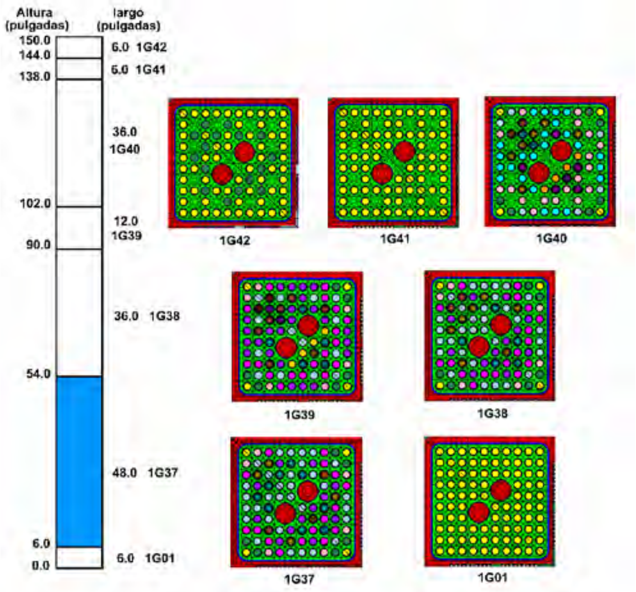


DIAGRAMA DE LA CARGA INICIAL DE COMBUSTIBLE

- + 109 barras de control
- 68 ensambles de uranio natural (0.711 % U235)
- 96 ensambles de medio enriquecimiento (1.76 % U235)
- 280 ensambles de alto enriquecimiento (2.19 % U235)

BWR



Paso 1

--	--	--	--		
--	--	4	--	--	
--	--	--	--	--	--
4	--	--	--	4	--
--	--	--	--	--	--
--	--	4	--	--	--

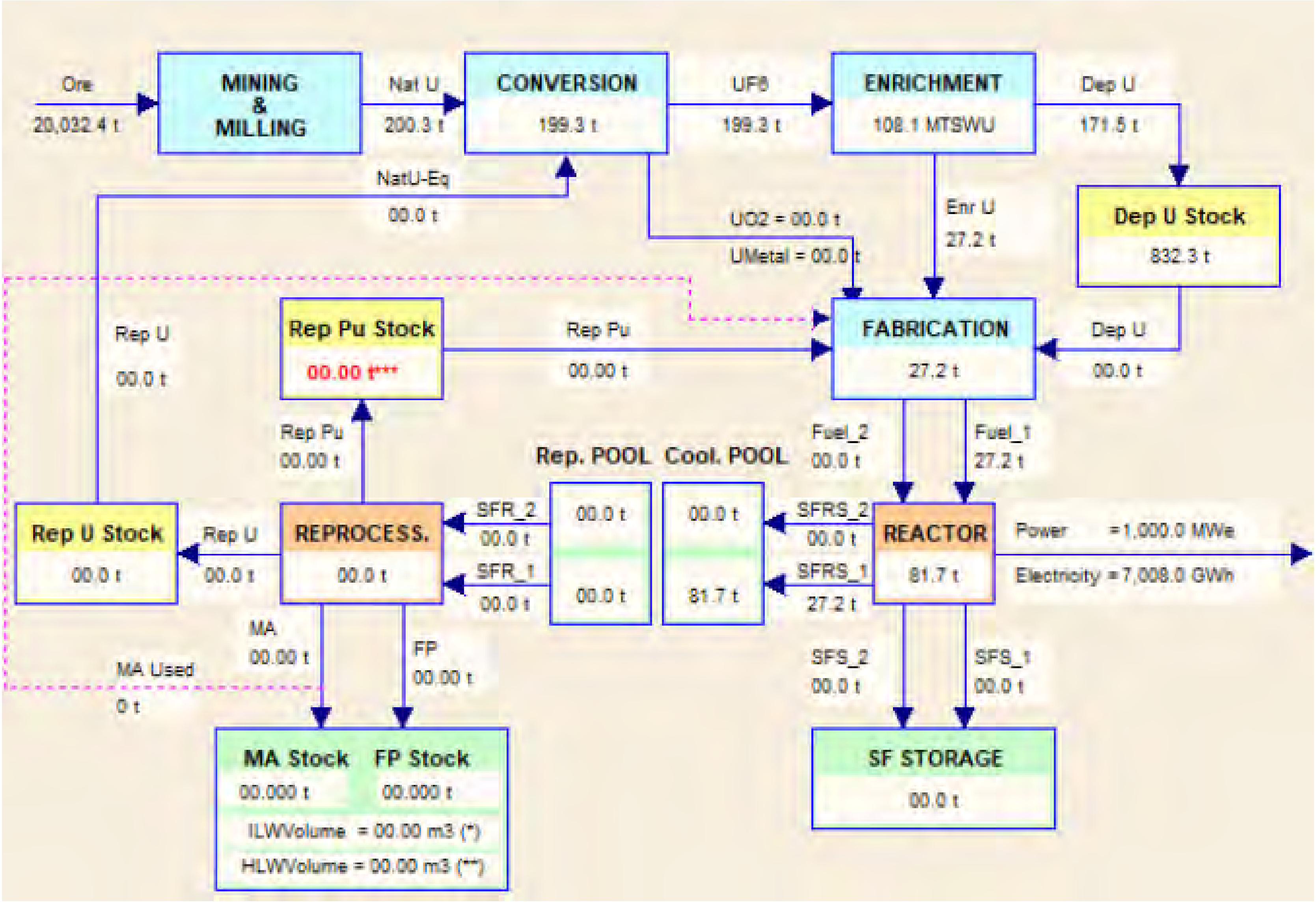
K= 0.99547
P= 2.967
MLHGR= 488.0
RAPLHGR= 0.922
MCPR= 1.38
FLOW= 94%

Paso 2

--	--	--	--		
40	--	10	--	--	
--	--	--	--	--	--
6	--	40	--	10	--
--	--	--	--	--	--
40	--	6	--	40	--

K= 0.99790
P= 2.497
MLHGR= 409.5
RAPLHGR= 0.825
MCPR= 1.43
FLOW= 94%

Requerimientos de uranio para una recarga de combustible



Nuclear Fuel Cycle Simulation System

https://infcis.iaea.org/NFCSS/modeling/material

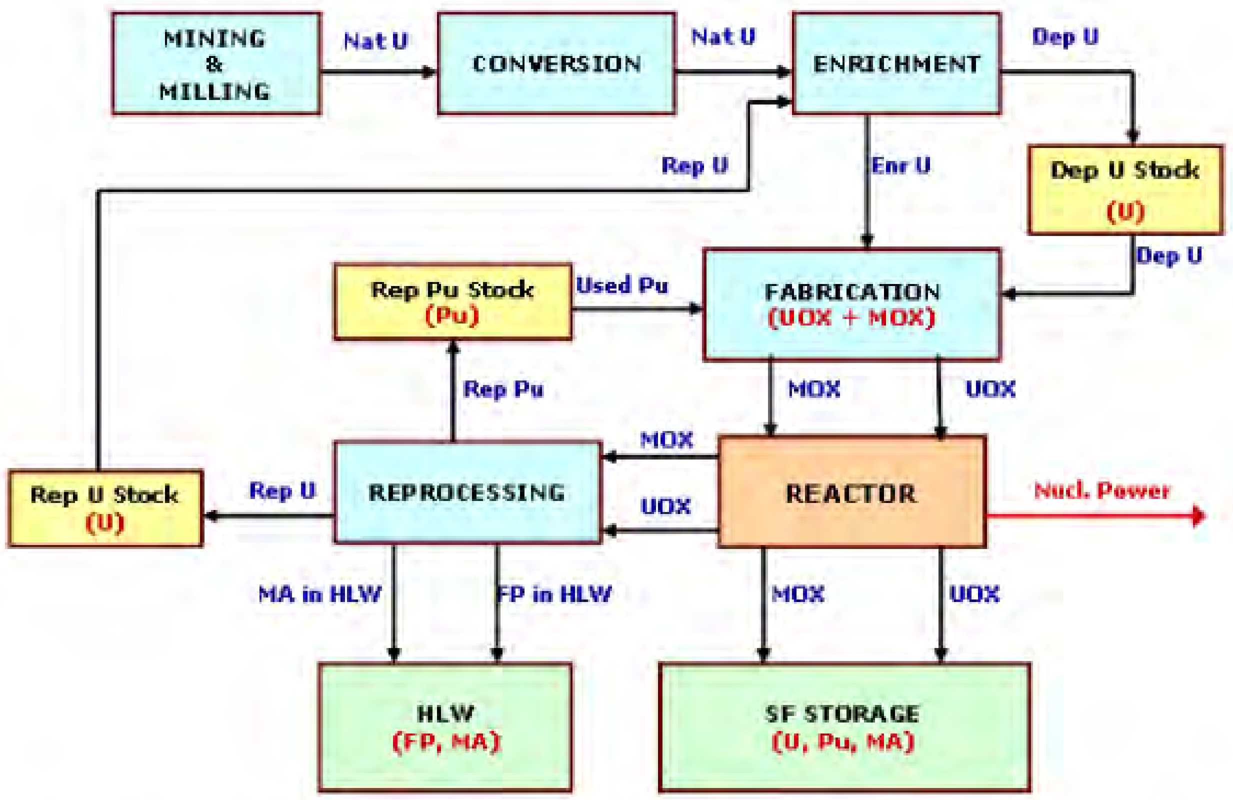


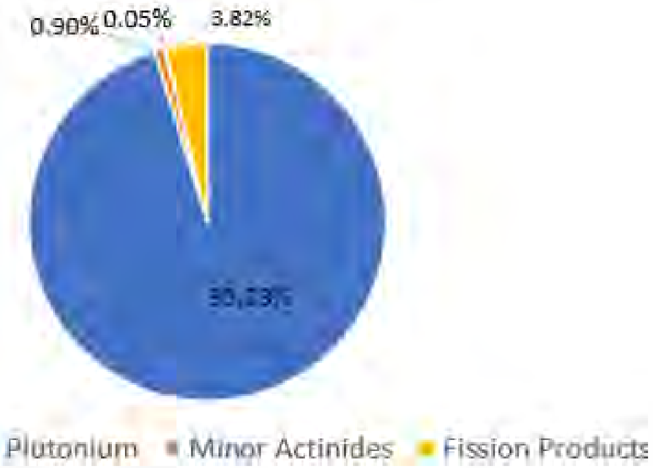
Illustration of material flow simulated in NFCSS (UOX + MOX Fuel use case).

Parte final del ciclo de combustible – *Back end*

Combustible gastado

U235	0.85%
U238	94.38%
Np237	0.04%
Pu238	0.01%
Pu239	0.50%
Pu240	0.22%
Pu241	0.12%
Pu242	0.05%
Am241	0.0029%
Am242	0.00001%
Am243	0.0080%
Cm242	0.0012%
Cm244	0.0021%
Total HM*	96.18%
Fission Products	3.82%

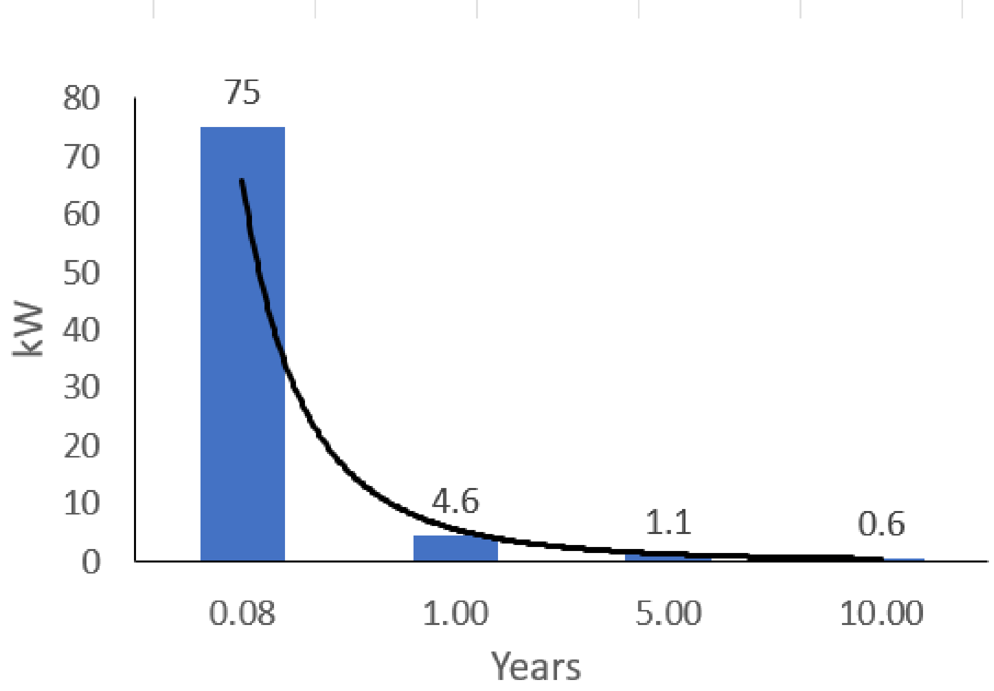
*HM = Heavy metal



Minor Actinides: Np, Am and Cm isotopes.

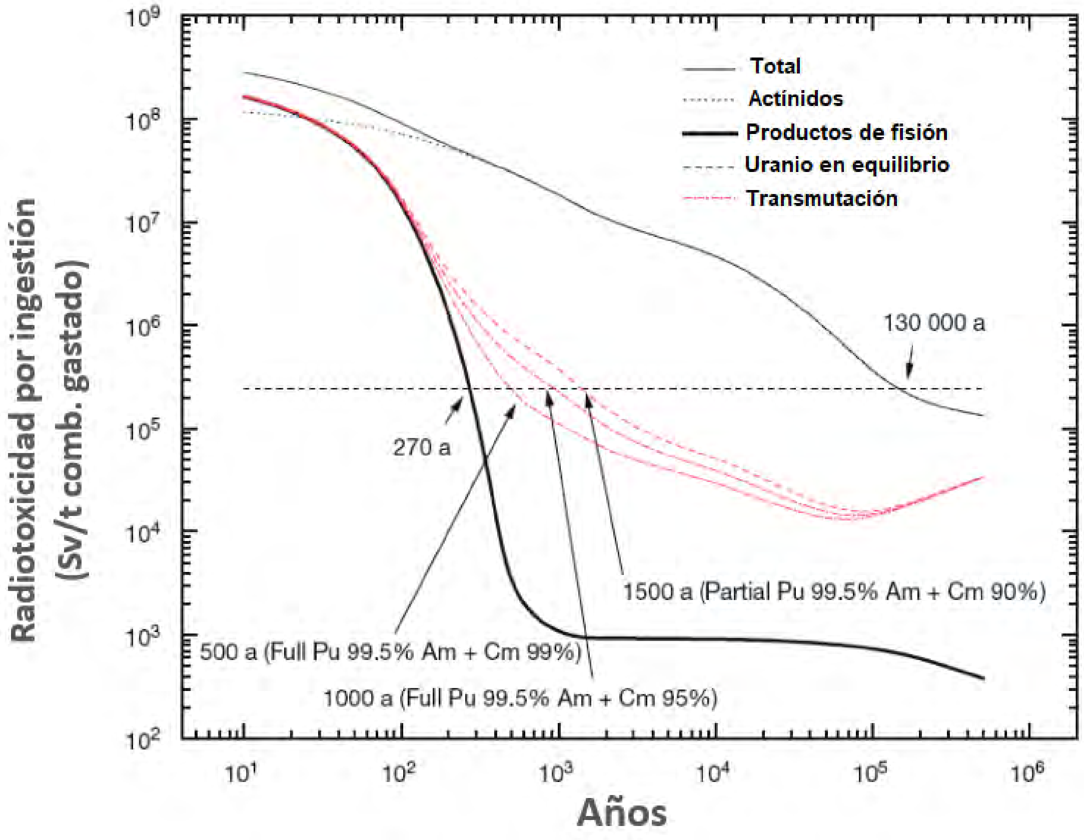
The plutonium isotopic composition breakdown is:

Pu238	1.32%
Pu239	55.37%
Pu240	24.44%
Pu241	13.53%
Pu242	5.34%



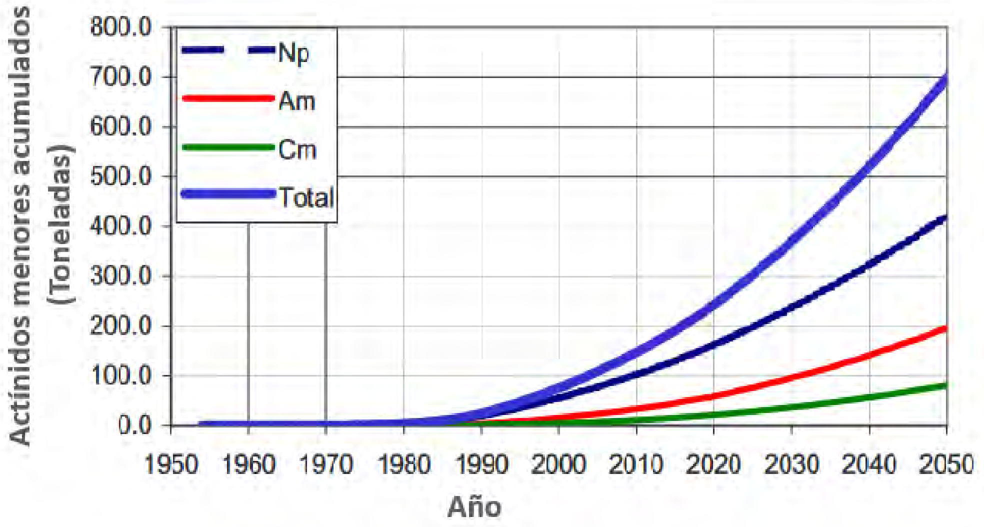
Calor de decaimiento típico de un ensamble combustible de un PWR

Combustible gastado



Radiotoxicidad del combustible gastado

Transuranic Elements	
Nuclide	Half-life
^{237}Np	$2.14 \cdot 10^6$ a
^{238}Pu	87.7 a
^{239}Pu	24100 a
^{240}Pu	6560 a
^{241}Pu	14.3 a
^{242}Pu	$3.74 \cdot 10^5$ a
^{241}Am	433 a
^{242m}Am	141 a
^{243}Am	7360 a
^{242}Cm	163 d
^{243}Cm	30.0 a
^{244}Cm	18.0 a
^{245}Cm	8500 a



Inventario de actínidos menores acumulados a nivel mundial

IAEA Nuclear Energy Series No. NF-T-4.6. (2009). Status of Minor Actinide Fuel Development. Vienna, Austria

Almacenamiento temporal de combustible gastado

Spent fuel storage in pools at nuclear energy plants

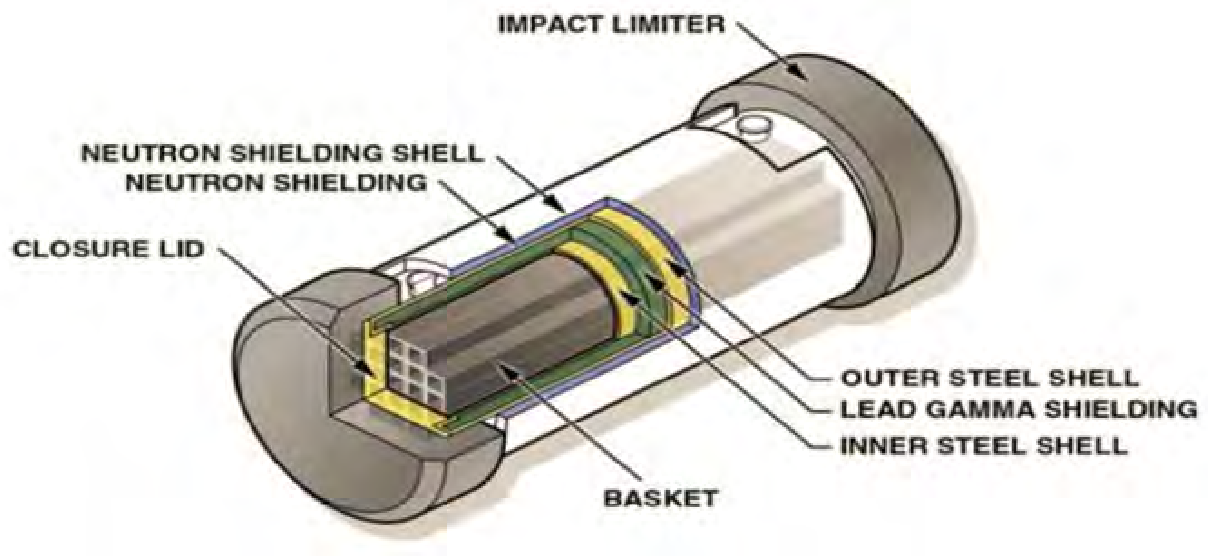
Nuclear Energy Institute:
https://www.youtube.com/watch?v=G_h4mCCzsbs

Dry cask storage for spent fuel at nuclear energy plants

Nuclear Energy Institute:
https://www.youtube.com/watch?v=rh6FeQWuhCs

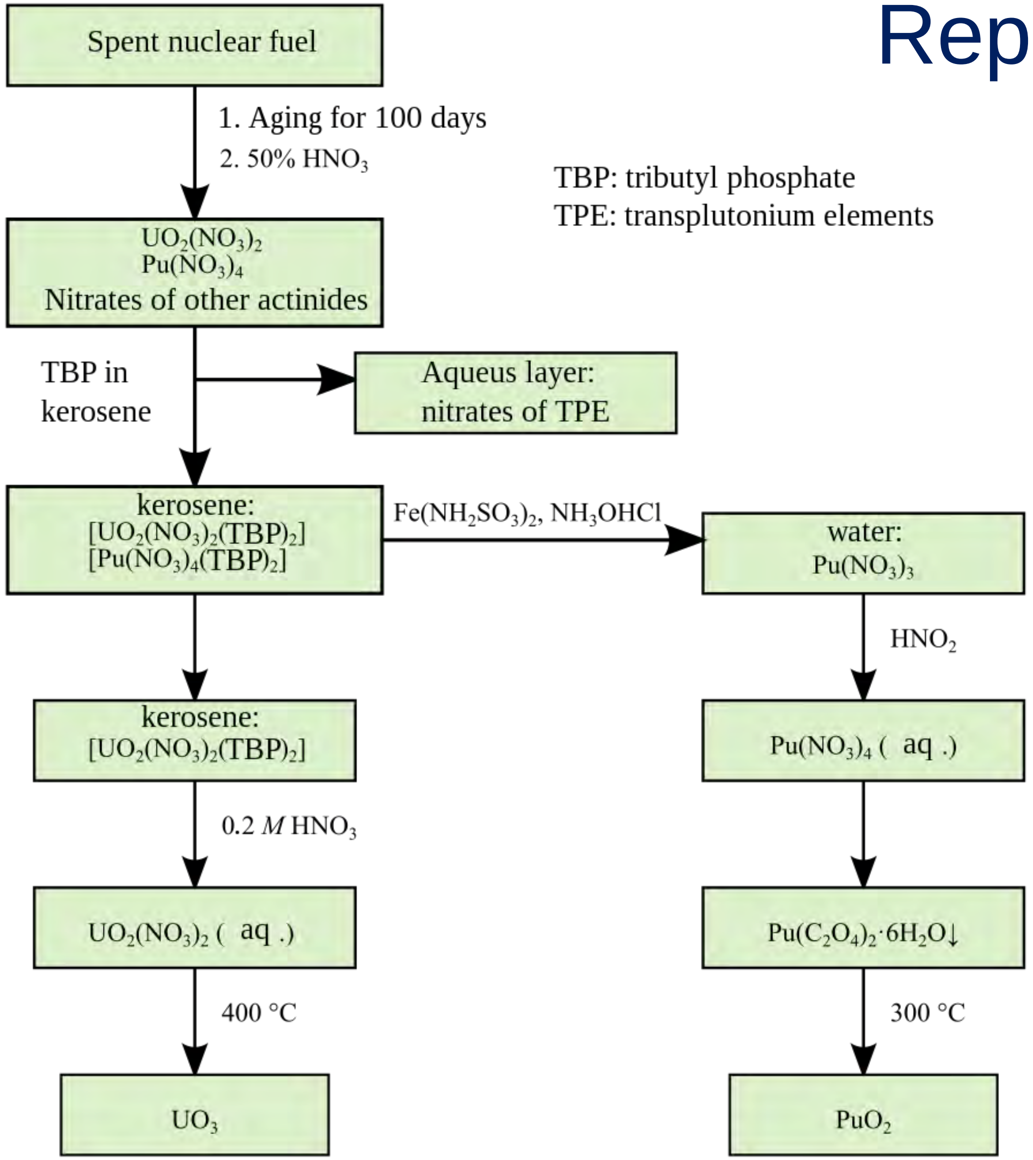
Transporte de combustible gastado

Transportation of a spent fuel cask by railcar.
https://www.ornl.gov/division/rnsd/projects/spent-nuclear-fuel-transportation



Spent nuclear fuel transportation cask.
https://www.ornl.gov/division/rnsd/projects/spent-nuclear-fuel-transportation

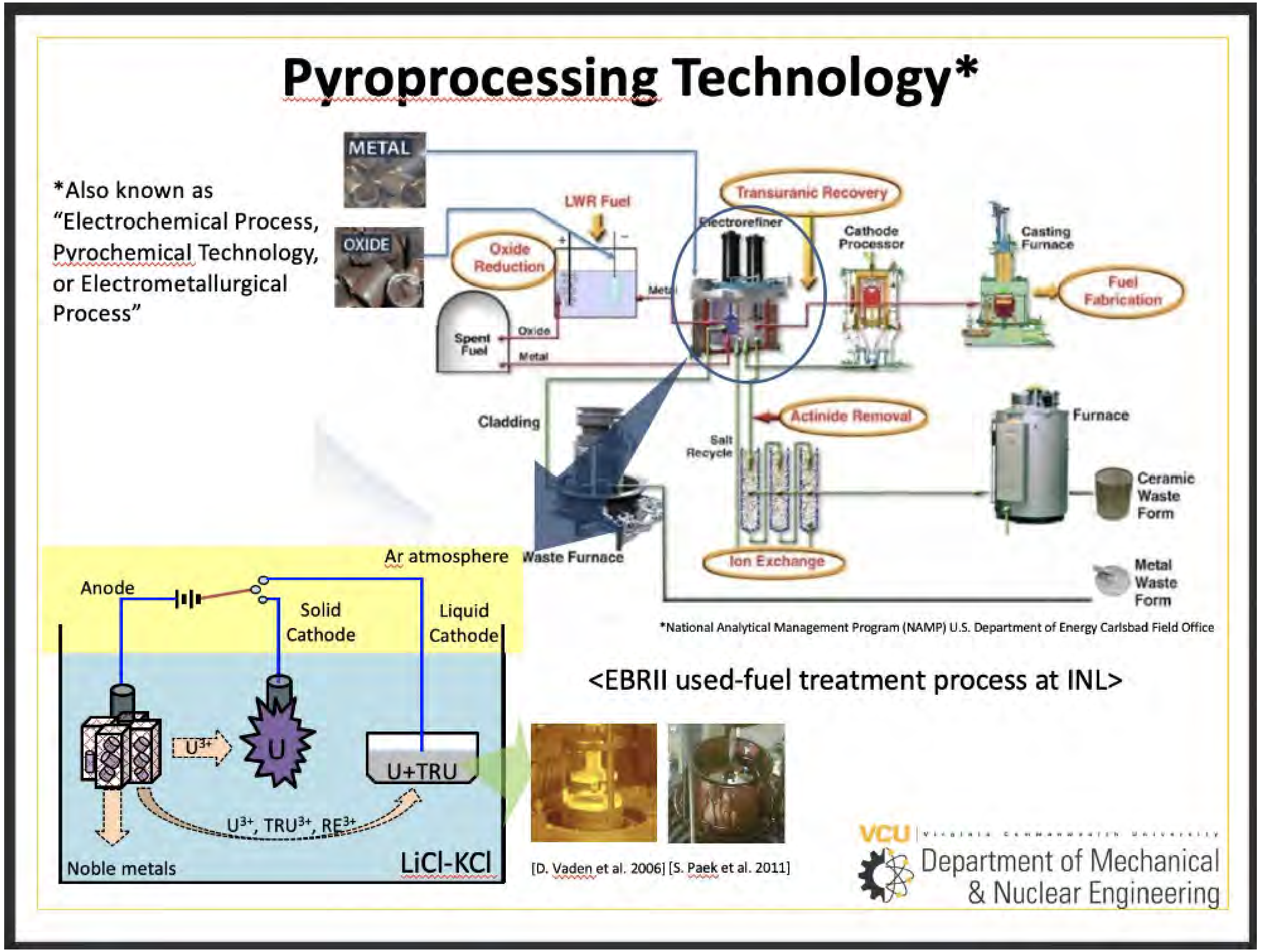
Reprocesamiento



PUREX process (simplified Flow sheet)

https://commons.wikimedia.org/wiki/File:Plutonium_and_uranium_extraction_from_nuclear_fuel-eng.svg

Reprocesamiento



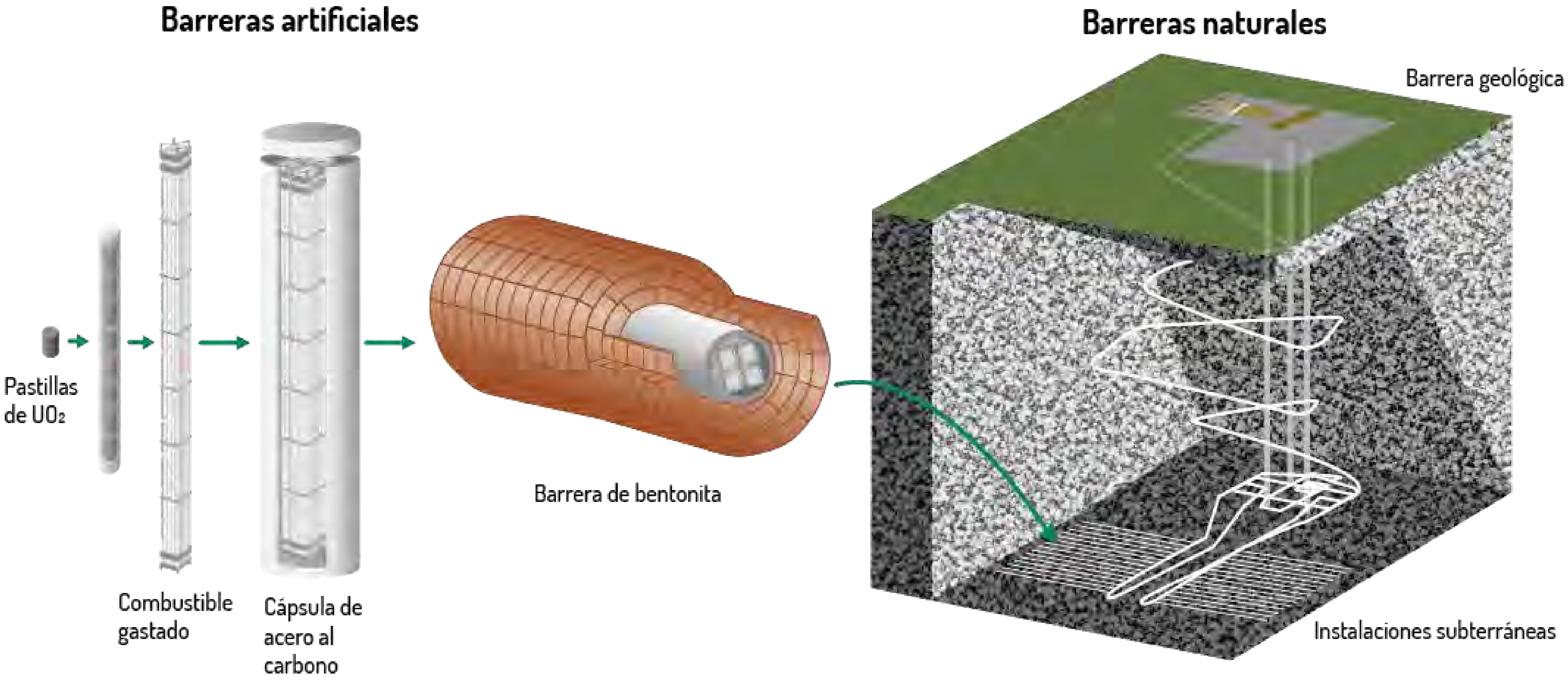
Pyroprocessing process.
http://people.vcu.edu/~sphongikaroon/laboratories.html

Reprocesamiento

Country ↑	Facility Name	Facility Type	Fuel Type	Facility Status	Scale	Design Capacity	Start of Operation	End of Operation
France	La Hague - UP2-800	Spent Fuel Reprocessing - aqueous route		In Operation	Commercial	1000 t HM/year	1996	
France	La Hague - UP3	Spent Fuel Reprocessing - aqueous route		In Operation	Commercial	1000 t HM/year	1990	
Russian Federation	RT-1 Plant	Spent Fuel Reprocessing - aqueous route		In Operation	Commercial	400 t U/year	1977	
United Kingdom	NDA Sellafield Magnox Reprocessing	Spent Fuel Reprocessing - aqueous route		In Operation	Commercial	1000 t U/year	1964	2020

https://infcis.iaea.org/NFCFDB/facilities

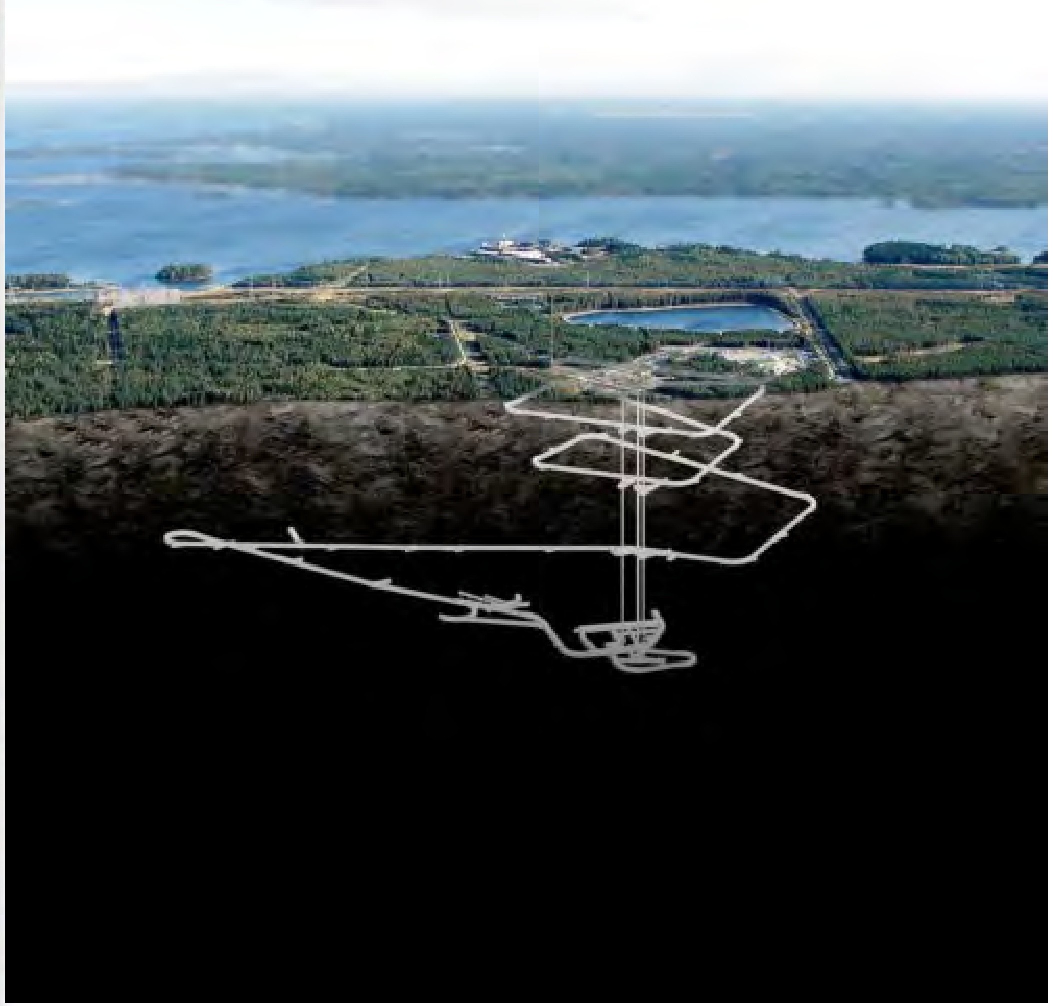
Almacenamiento geológico profundo



https://www.enresa.es/esp/inicio/actividades-y-proyectos/residuos-de-alta-actividad

Onkalo: Primer Almacén Geológico Profundo del Mundo

Finlandia



https://rinconeducativo.org/es/noticias/onkalo-primer-almacen-geologico-profundo-del-mundo/

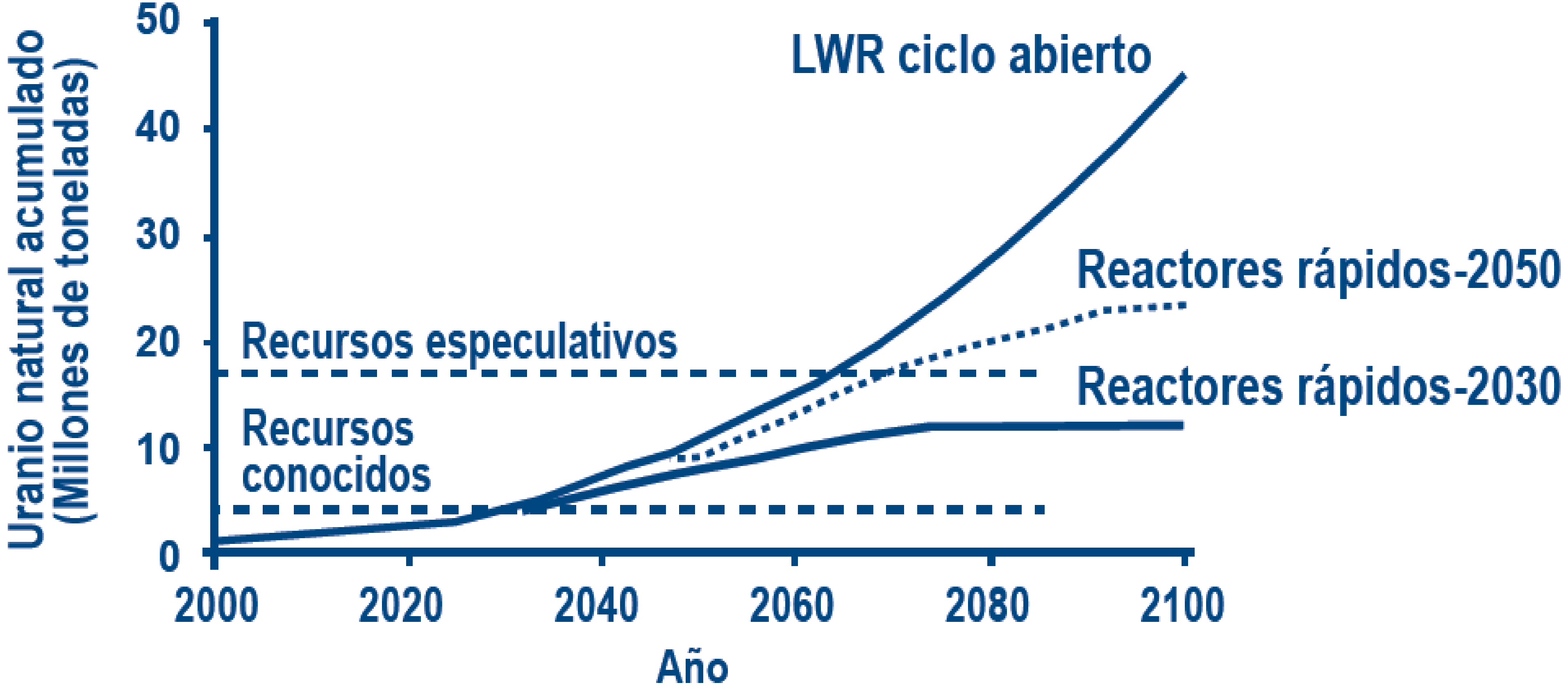
Ciclo de Combustible Nuclear Avanzado

Utilization of Natural Resources

The strongest argument for reprocessing and recycling is the improved utilization of the natural uranium resource.

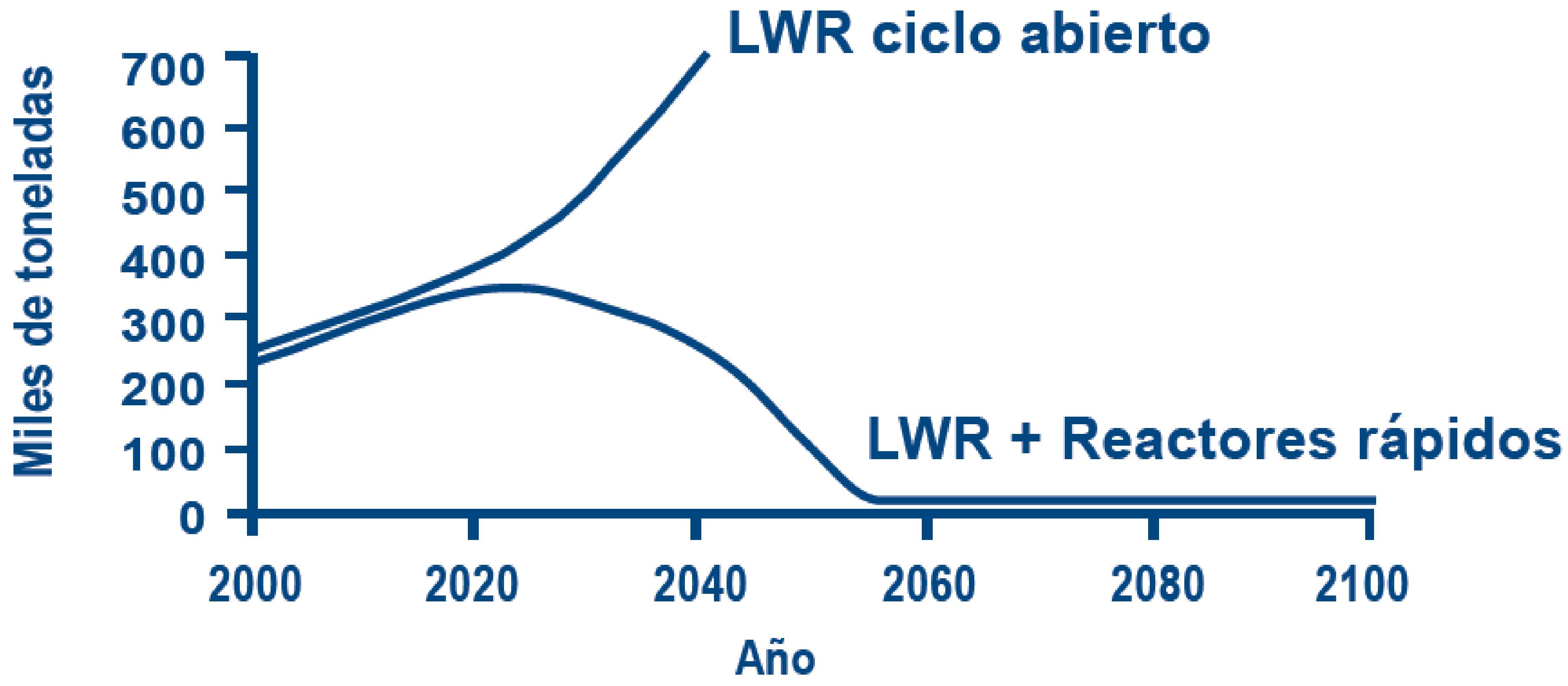
REDUCTION IN URANIUM DEMAND	
Without recycling	0%
Recycling in light water reactors	25%
Multiple recycling in fast reactors	95%

Utilización de uranio



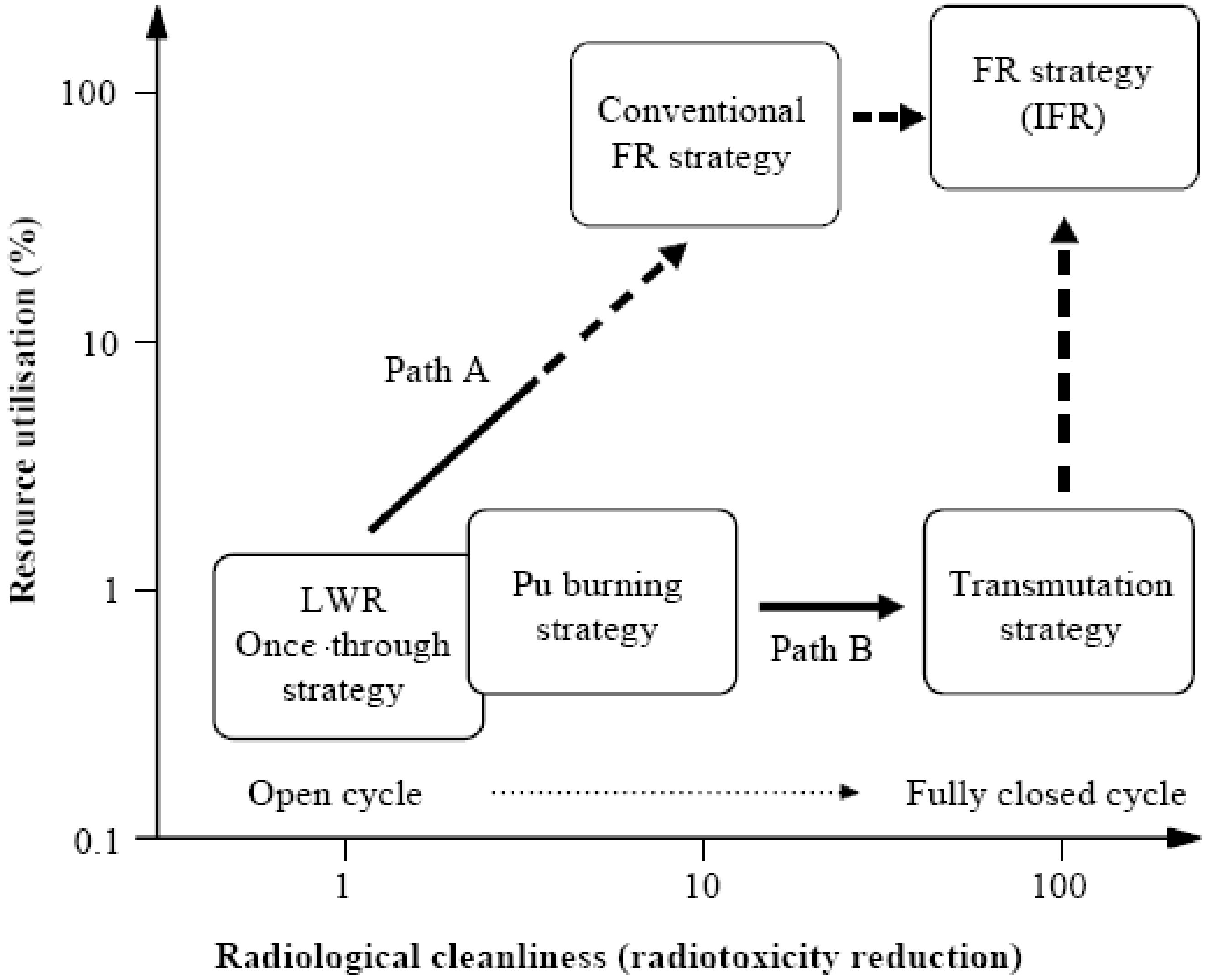
J.L. François. El ciclo de combustible y la sostenibilidad de la energía nuclear. Revista Eficiencia Energética, Año 10, Número 35, Diciembre, 2022.

Masa de combustible gastado acumulado

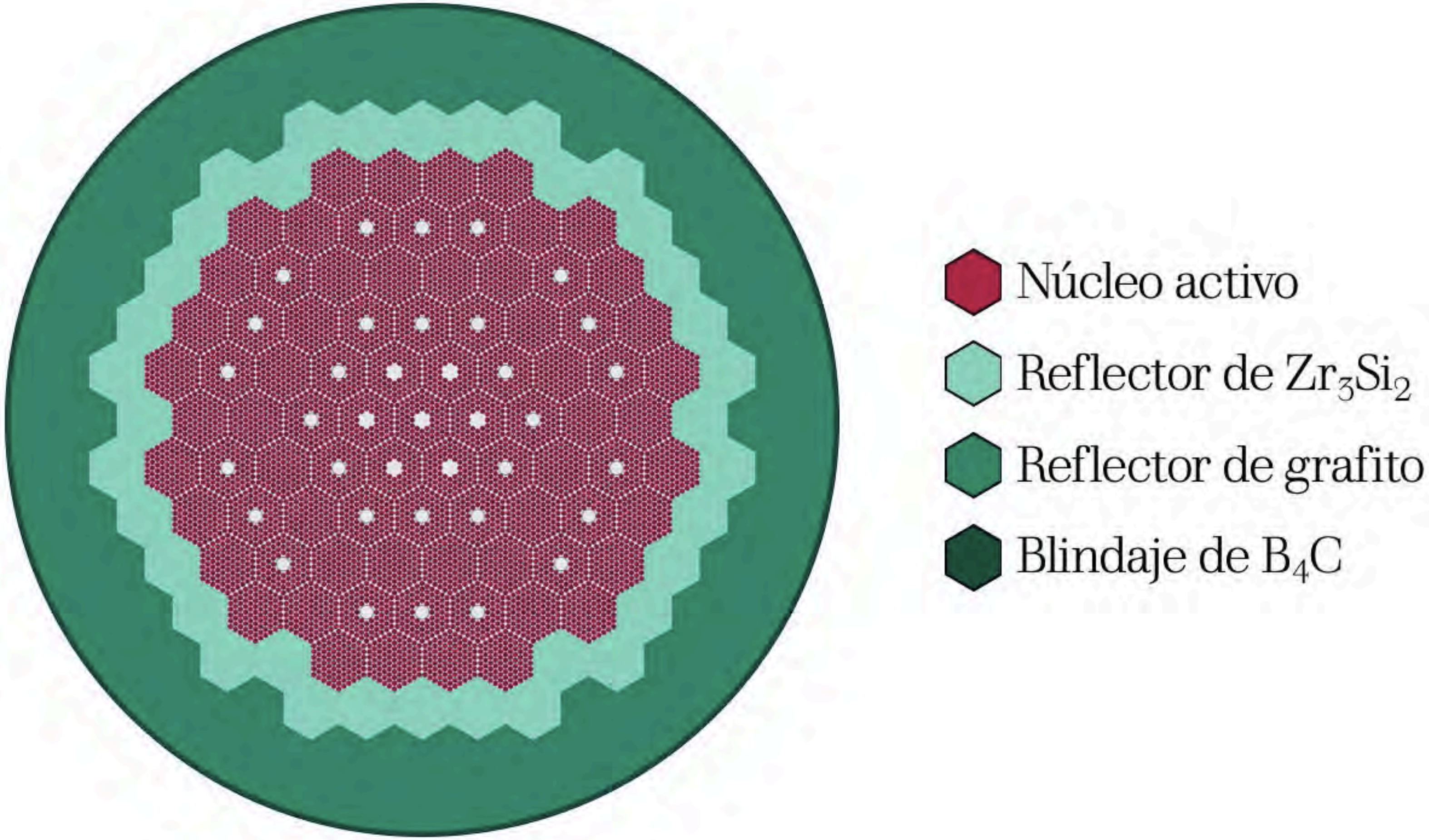


J.L. François. El ciclo de combustible y la sostenibilidad de la energía nuclear. Revista Eficiencia Energética, Año 10, Número 35, Diciembre, 2022.

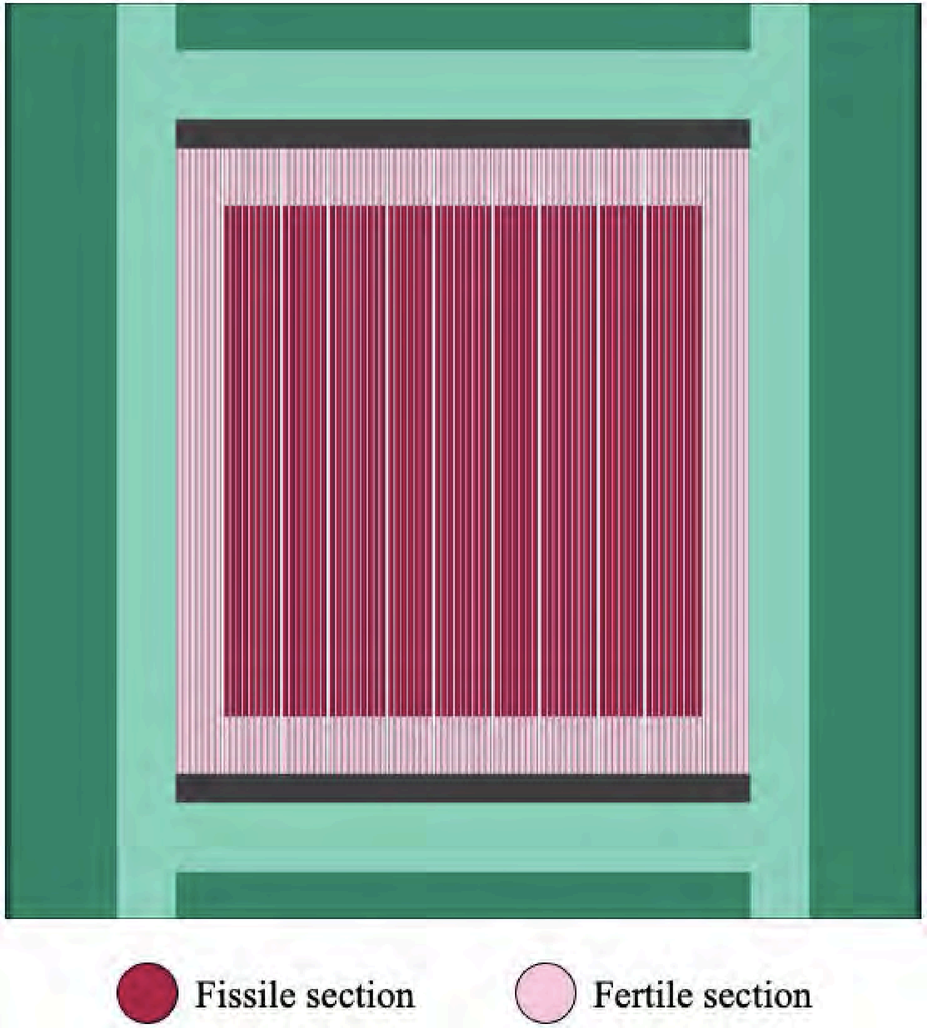
Estrategias de utilización del combustible nuclear

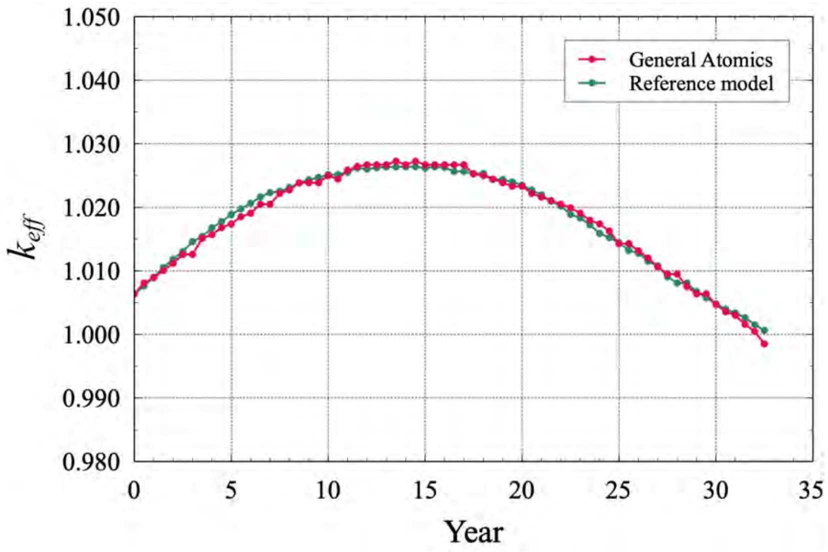


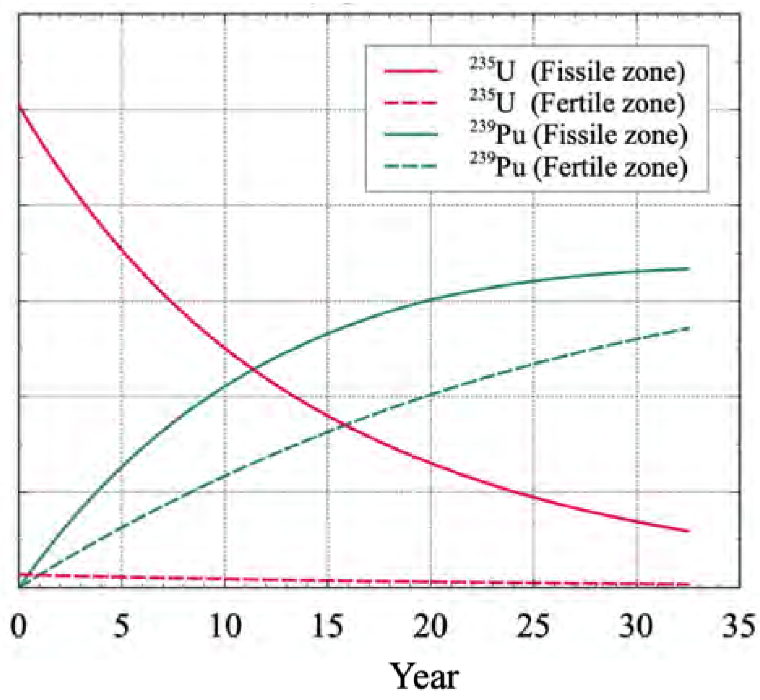
Diseño del núcleo del EM^2



Vista transversal del núcleo del EM^2







E. Morones-García , J.L. François. Alternatives to the burnup strategy and fuel material of the EM2 modular reactor. Annals of Nuclear Energy. Vol. 182, 109638, pp. 1-15, 2023.
https://doi.org/10.1016/j.anucene.2022.109638.

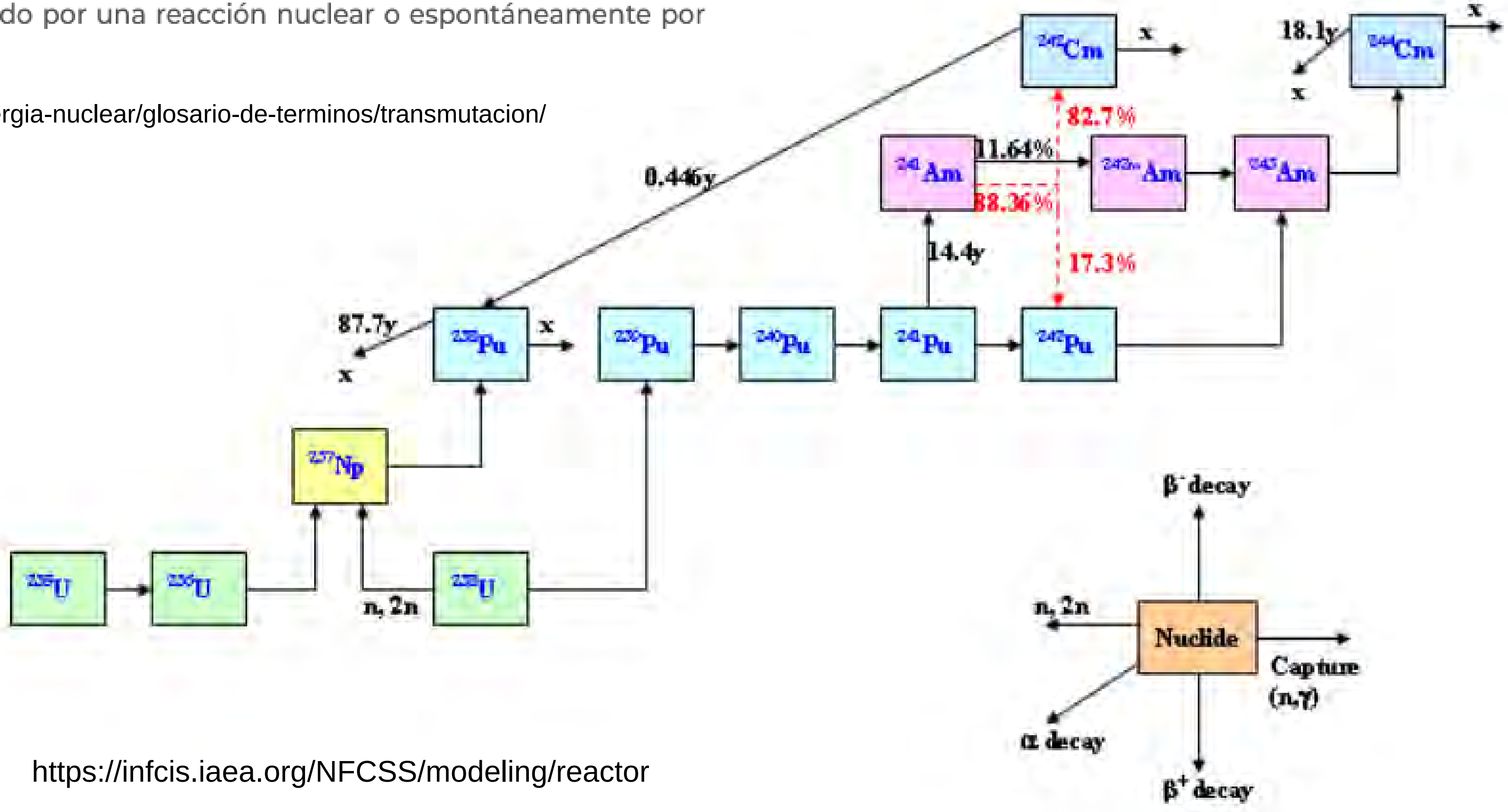
Transmutación y decaimiento radioactivo

Glosario de términos

Transmutación

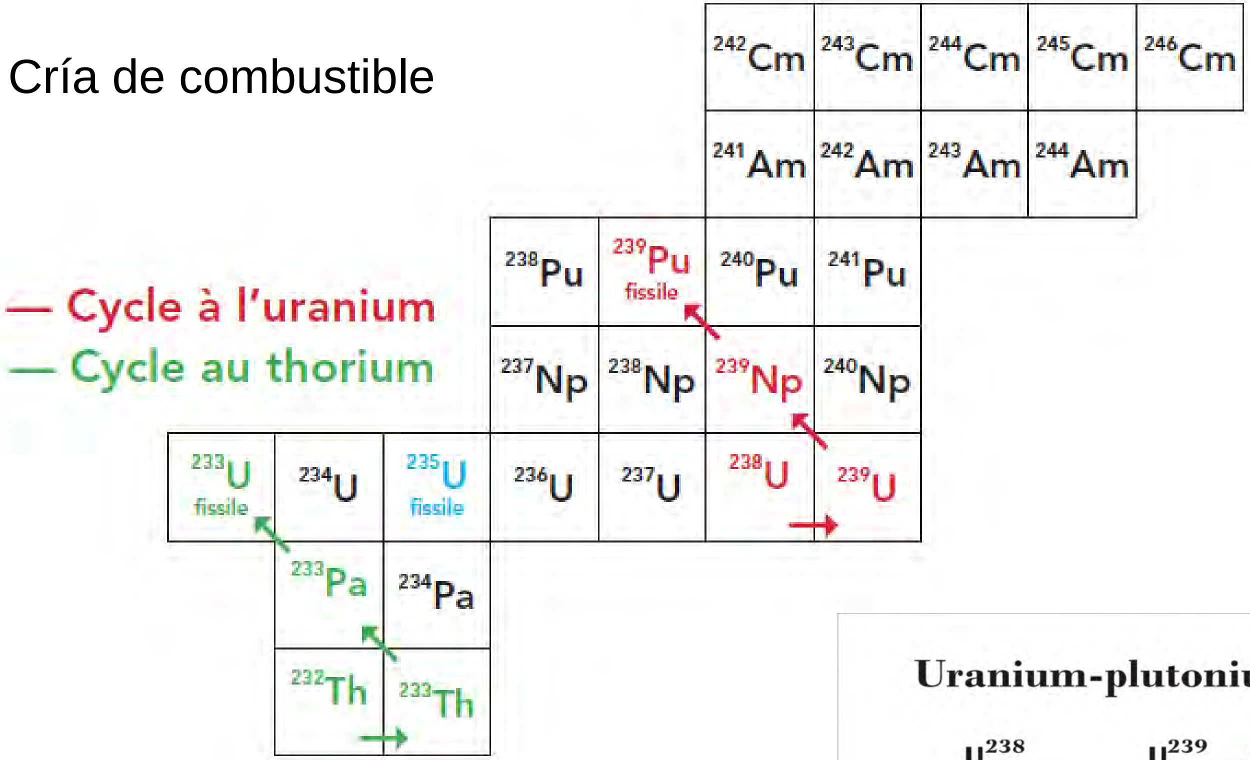
En física nuclear, conversión de un elemento químico en otro. Supone un cambio en la estructura del núcleo atómico inducido por una reacción nuclear o espontáneamente por una desintegración radiactiva.

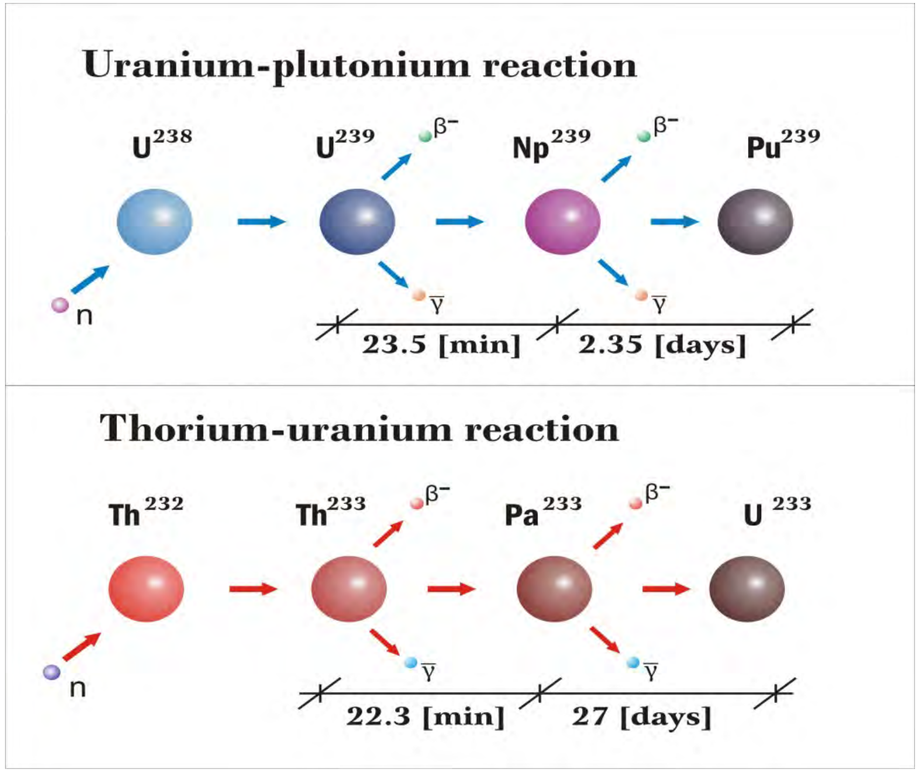
https://www.foronuclear.org/descubre-la-energia-nuclear/glosario-de-terminos/transmutacion/



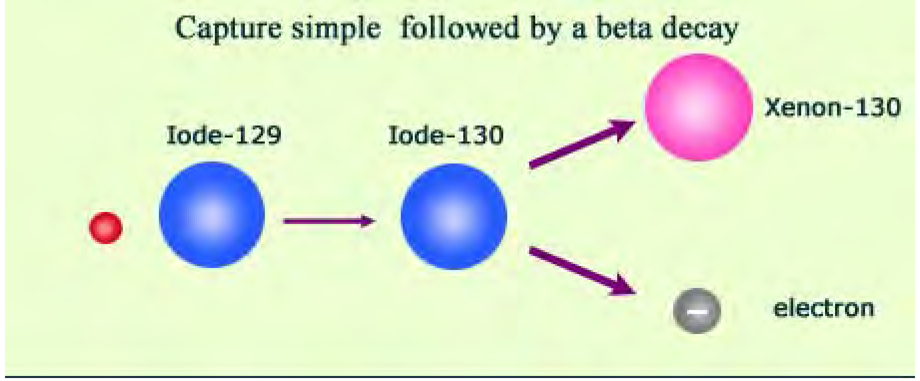
https://infcis.iaea.org/NFCSS/modeling/reactor

Cría de combustible





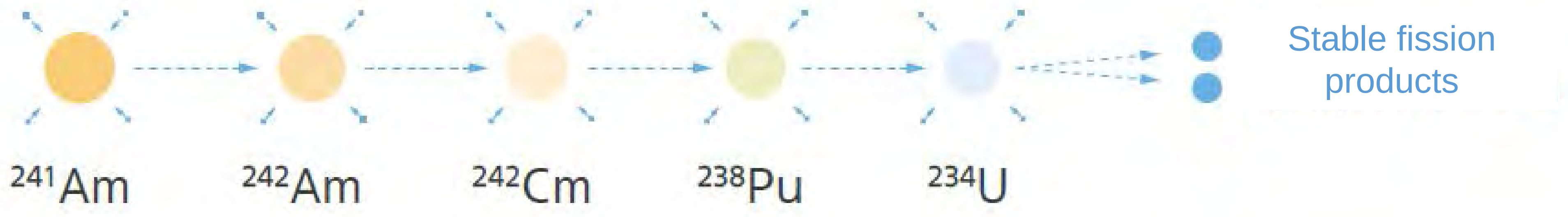
Trasmutación



MA transmutation is a unique fast reactor feature

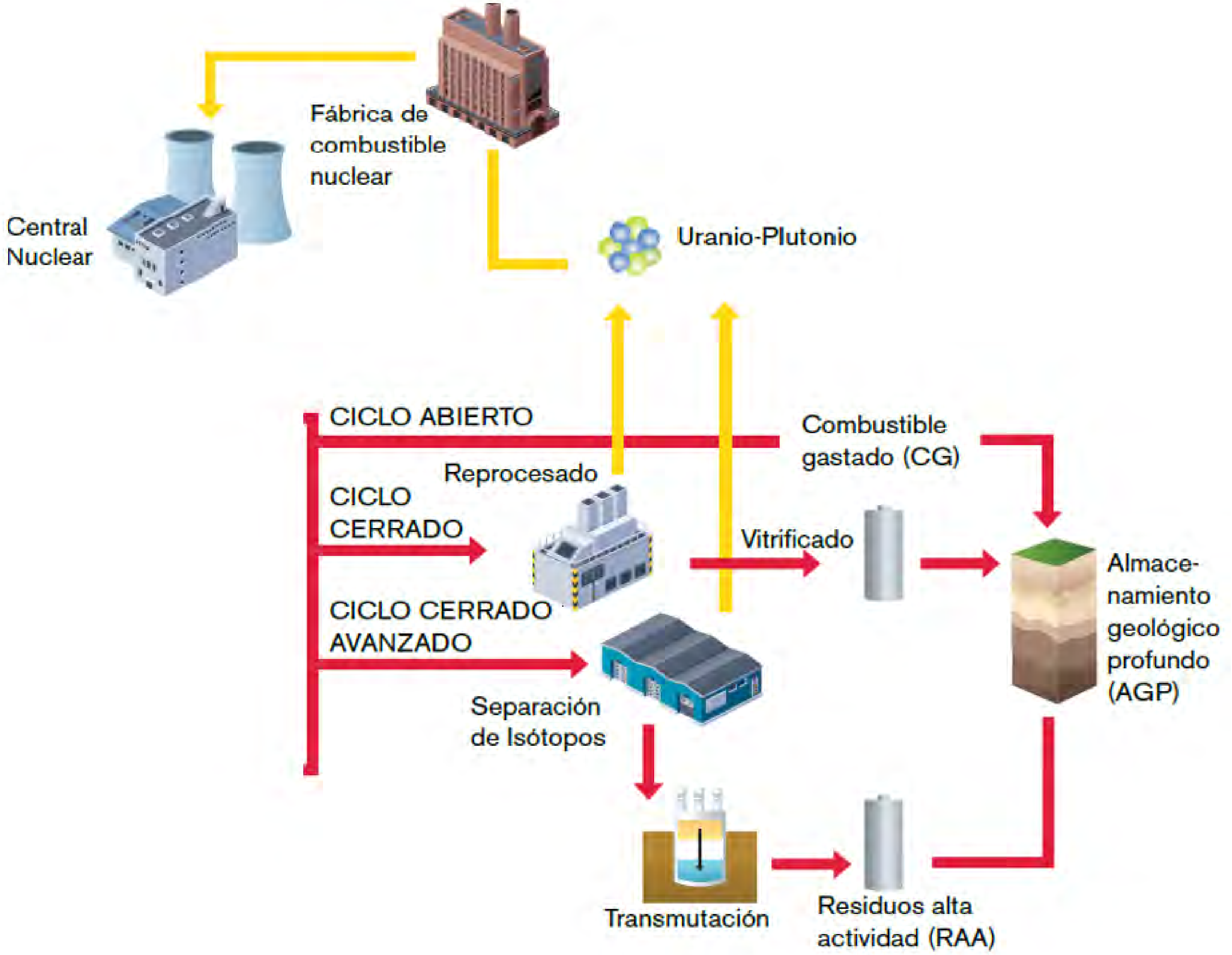
Minor actinides (americium, neptunium, curium) are fission products of uranium and plutonium. Their total content in SNF is less than 1%. However, it is their impact that determines the activity and heat release of highly-radioactive waste after 300 years of holdup.

- ROSATOM proposes to dispose minor actinides by burning them in fast reactors.
- ROSATOM's fleet of operating fast reactors (BN-600, BN-800) as well as those which are under construction and development (BN-1200M, BREST-300) applicable for minor actinides burning on an industrial scale.
- Technology is proven in the certain tests in the research reactors (BOR-60).

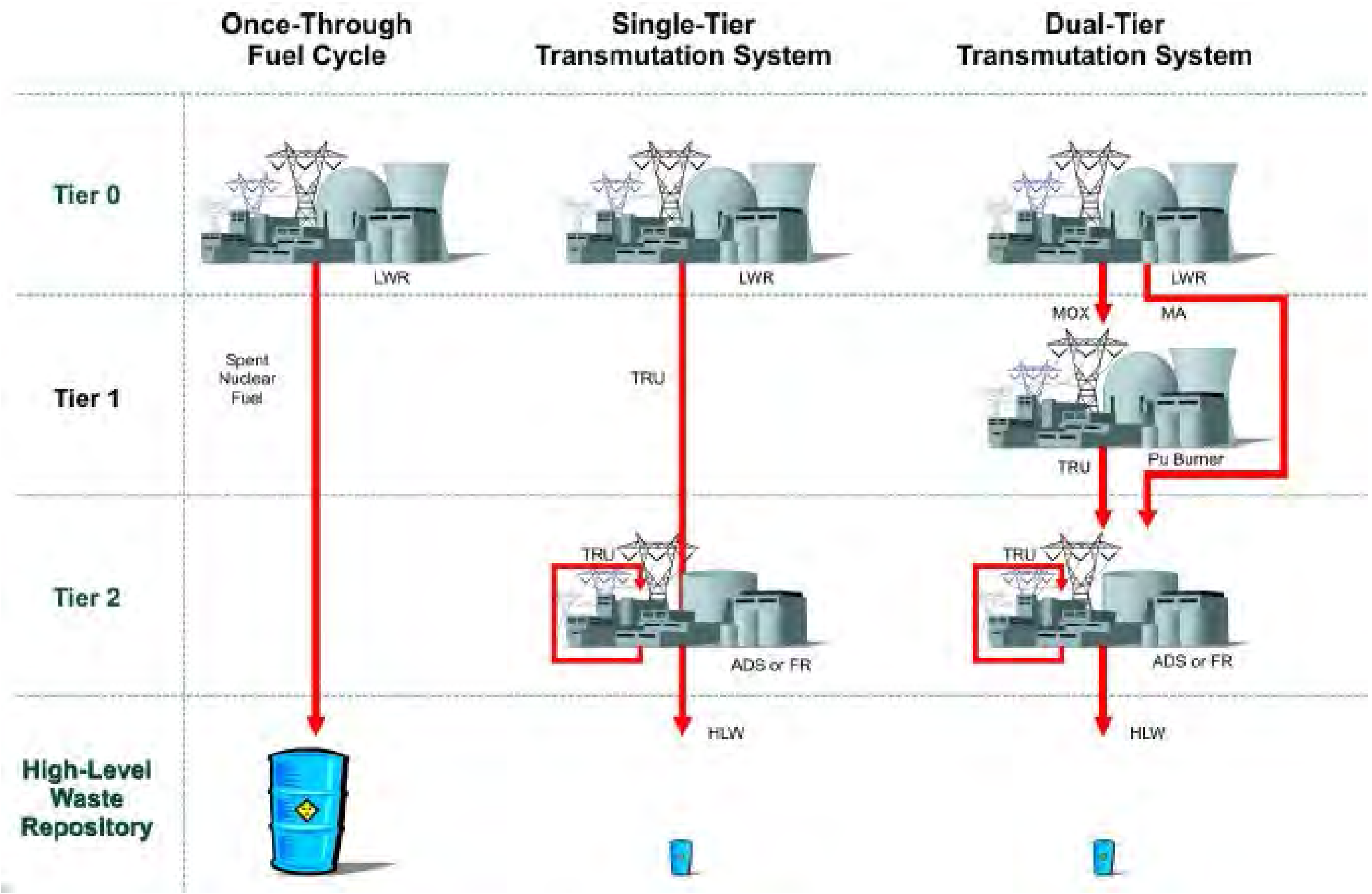


MA transmutation allows to dispose of the most long-lived radioactive waste fraction

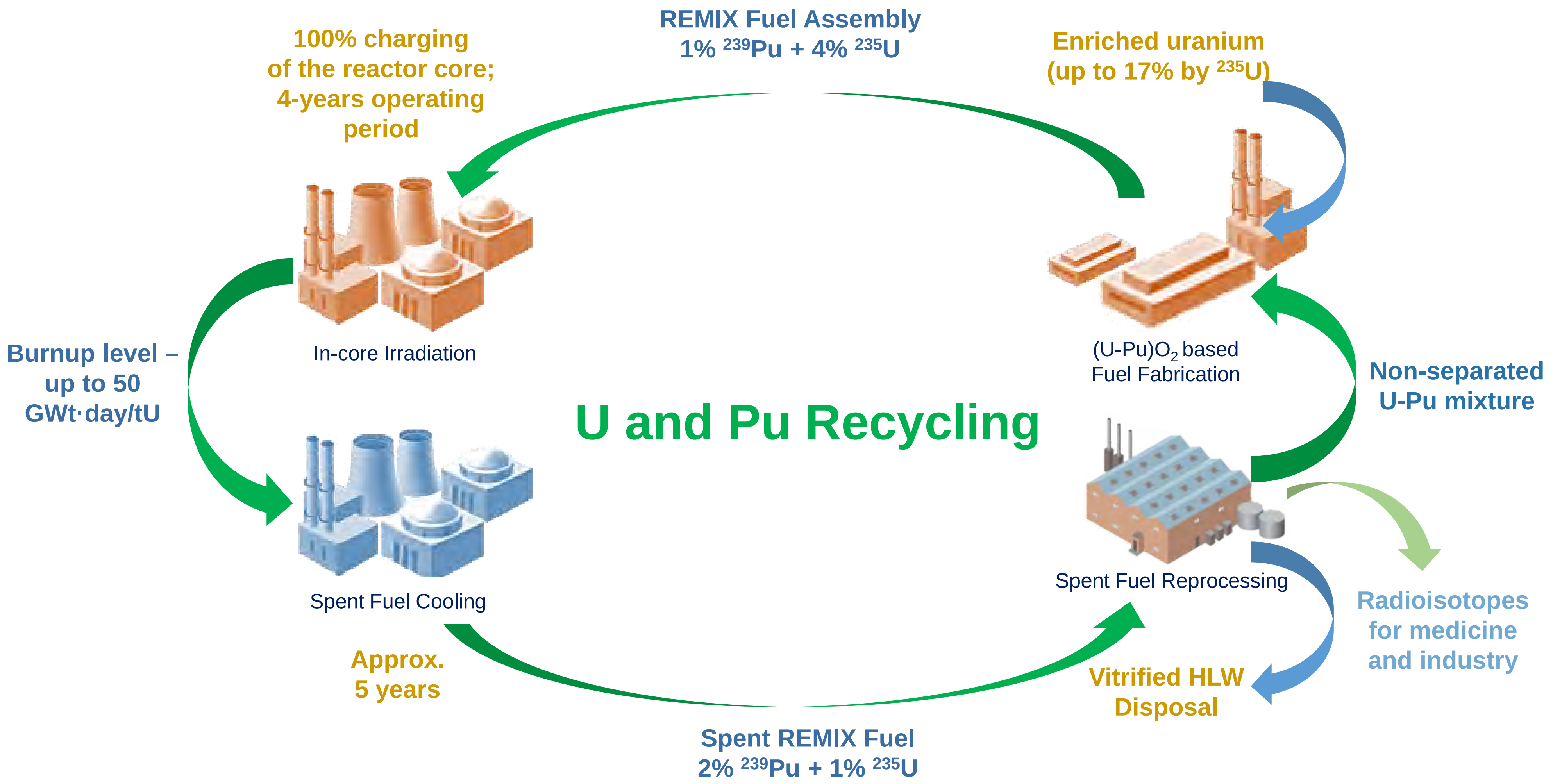
Ciclo de Combustible Nuclear Avanzado



Ciclos de Combustible Avanzado



Balanced Approach to Fissile Materials



World Nuclear Fuel Cycle conference, Abu Dhabi, United Arab Emirates, April 06, 2016

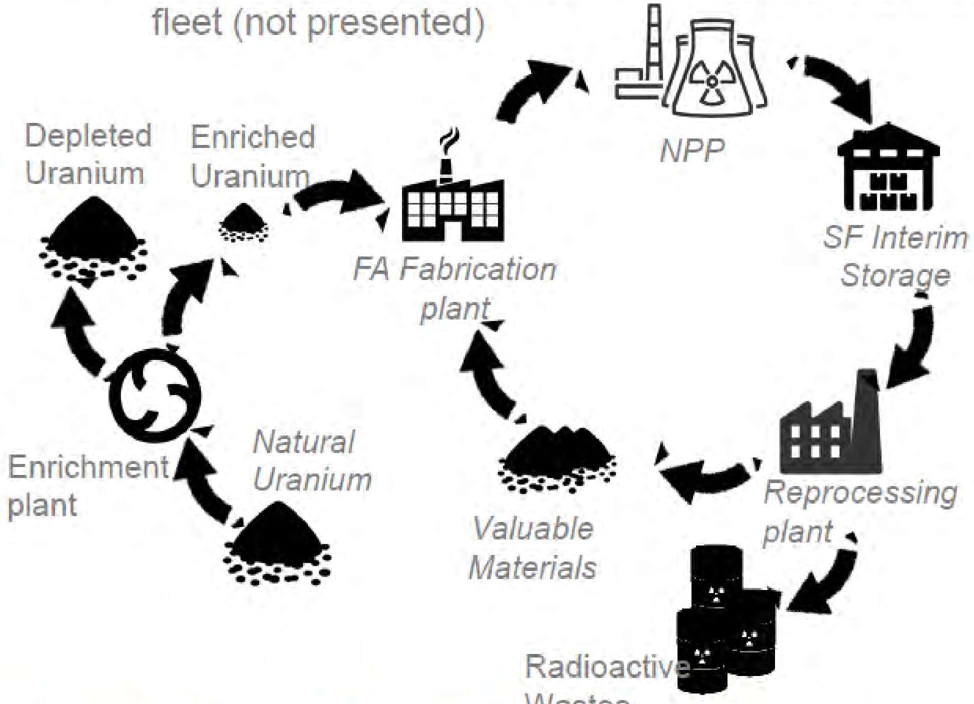
COMPARISON OF INDUSTRIAL SCENARIOS

HYPOTHESIS

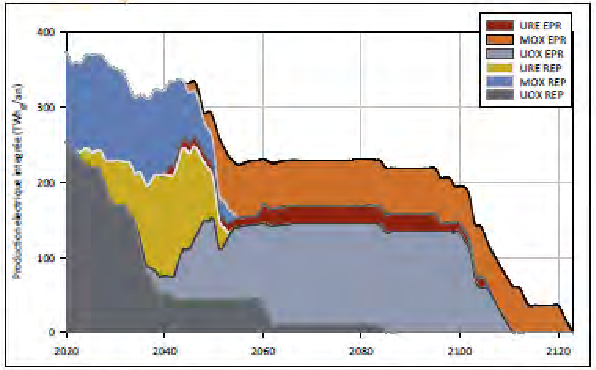
Code used to perform these evaluations: COSI

Simulated Scenarios: Optimized (transitioning towards) open cycle, Monorecycling cycle, Multirecycling cycle

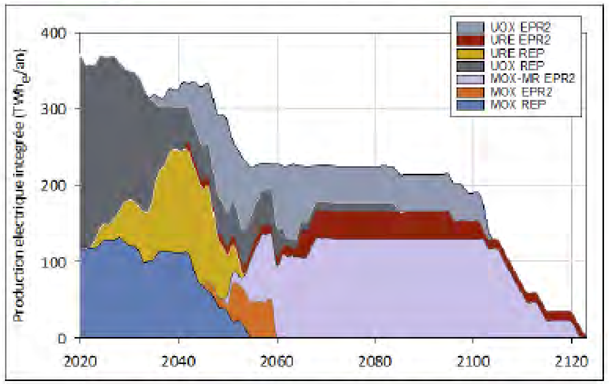
- Installed capacity of the new fleet : 30 GWe (18 reactors)
- New MOX2 FA into reactor starting from 2050 based on MOX-MR only or MOX-MR then MIX from 2070
- Partial fuel management (50% MOX-MR or 60% MIX)
- Work ongoing on the transition towards a future SFR fleet (not presented)



Mono Recycling

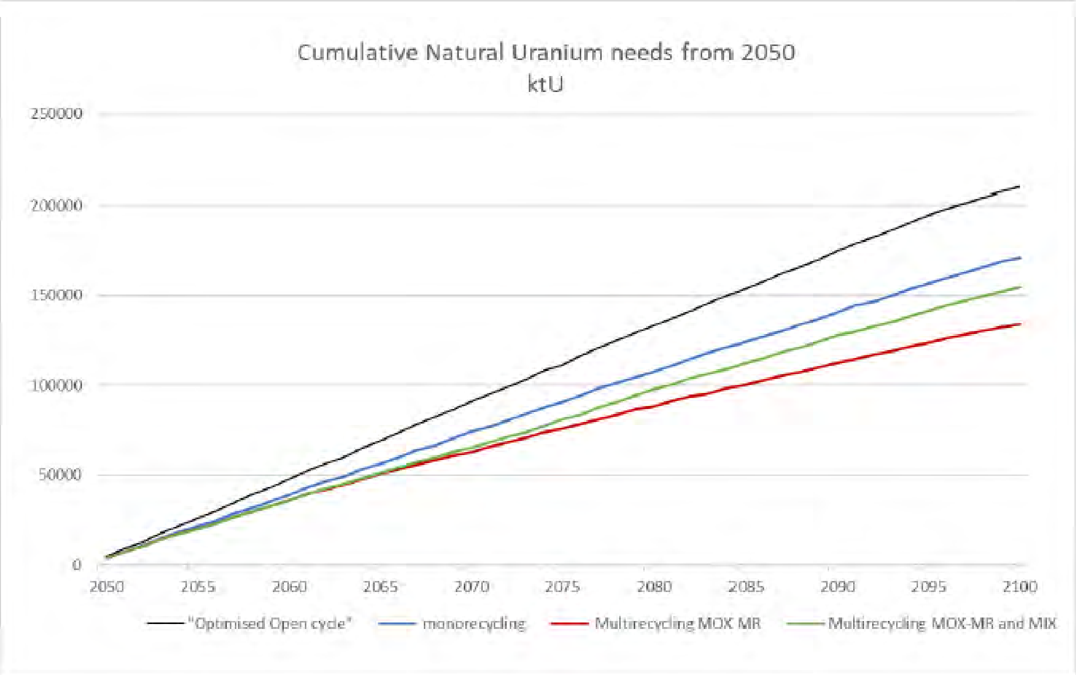


Multi Recycling



EDF framatome cea orano

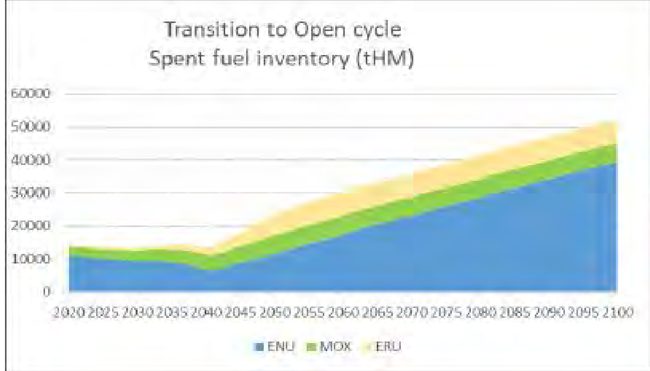
RESULTS ON NATURAL URANIUM CONSUMPTION

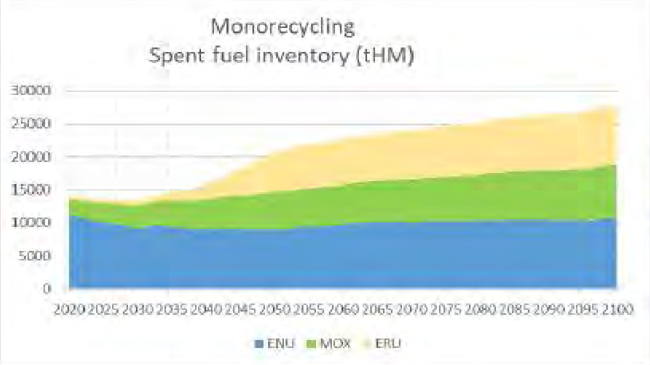


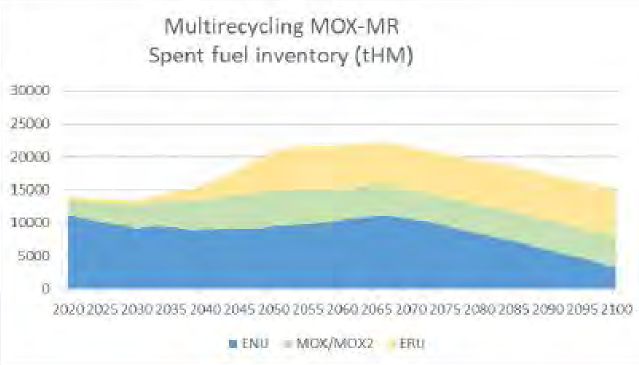
Average Natural Uranium Consumption at equilibrium

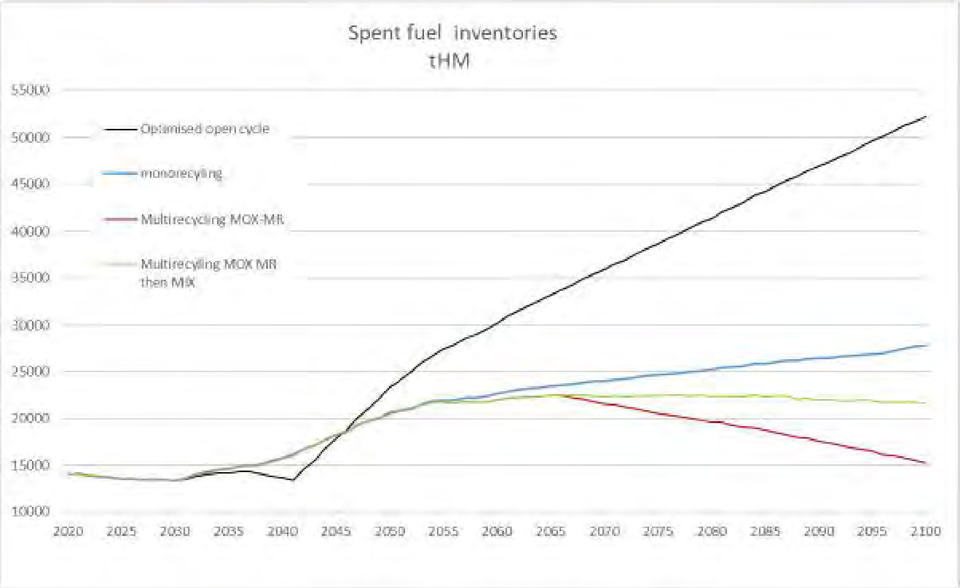
Optimized open Cycle	+ 4,17 kt/y
Mono Recycling Cycle	+ 3,33 kt/y
Multi Recycling Cycle	+ 2,44 kt/y

RESULTS ON SPENT FUEL INVENTORIES



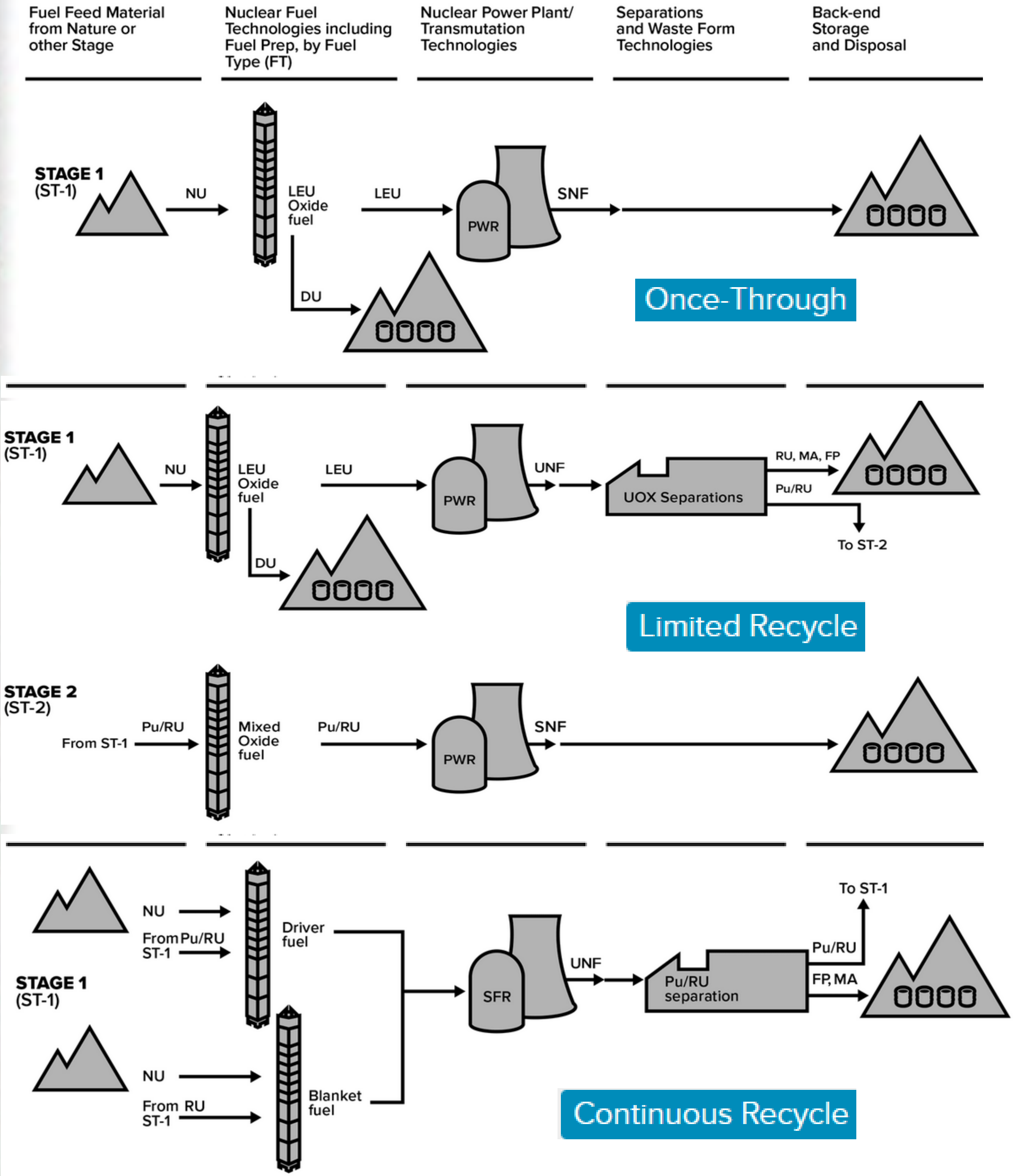






Total SF inventory around 2090

Optimized open Cycle	47kt + 480t/y
Mono Recycling Cycle	26,5kt + 120 t/y
Multi Recycling Cycle	17,5kt-190t/y



	Once-through default
Reactor Capital Recovery Cost ($/MWh)	30.6
Fuel Cost ($/MWh)	8.3
Reactor Operation And Maintenance Cost ($/MWh)	10.6
	=====
Total Levelized Cost of Electricity ($/MWh)	**49.5**

	Once-through default	Current Data
Reactor Capital Recovery Cost ($/MWh)	30.6	30.6
Fuel Cost ($/MWh)	8.3	12.6
Reactor Operation And Maintenance Cost ($/MWh)	10.6	10.6
	=====	=====
Total Levelized Cost of Electricity ($/MWh)	**49.5**	**53.7**

	Once-through default	Current Data
Reactor Capital Recovery Cost ($/MWh)	30.6	32.8
Fuel Cost ($/MWh)	8.3	8.3
Reactor Operation And Maintenance Cost ($/MWh)	10.6	10.8
	=====	=====
Total Levelized Cost of Electricity ($/MWh)	**49.5**	**51.9**

Argonne NATIONAL LABORATORY

Nuclear Fuel Cycle Evaluation and Screening

https://fuelcycleevaluation.inl.gov/SitePages/Home.aspx

Fuel Cycle Metrics and Values from Evaluation and Screening Study

Metric	Units	Once-Through	Limited Recycle	Continuous Recycle
Levelized Cost of Electricity at Equilibrium (LCAE)[a]	($/MWe-hr)	49.5	53.7	51.9
95% Confidence interval of the LCAE	($/MWe-hr)	30-60	25-65	25-65
Natural uranium required per energy generated	(t/GWe-yr)	188.6	171.2	1.3
Natural thorium required per energy generated	(t/GWe-yr)	0[b]	0[b]	0[b]
Mass of depleted uranium + recovered uranium disposed per energy generated	(t/GWe-yr)	166.7	167.7	0[b]
Mass of spent nuclear fuel and high-level radioactive waste disposed per energy generated	(t/GWe-yr)	21.9	3.4	1.3
Activity of spent nuclear fuel and high-level radioactive waste at 10 years per energy generated	(Ci/GWe-yr)	12,700,000	12,100,000	8,620,000
Activity of spent nuclear fuel and high-level radioactive waste at 100 years per energy generated	(Ci/GWe-yr)	1,340,000	1,330,000	1,030,000
Activity of spent nuclear fuel and high-level radioactive waste at 100,000 years per energy generated	(Ci/GWe-yr)	1,650	1,320	728

a Mean value using the default cost values, uncertainties are substantially larger than the differences

b Zero by definition for the selected fuel cycles

Nuclear Fuel Cycle Cost Calculator. https://cnpce.ne.anl.gov/cgi-bin/qnecost?select=benefits&id=ObcetDmnzwd0bAmZ

Gracias por su atención

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